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Aarts

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(54) **AUDIO SYSTEM**

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This patent is subject to a terminal disclaimer.

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(22) Filed: **Oct. 20, 1998**

Related U.S. Application Data

(63) Continuation-in-part of application No. 08/851,302, filed on May 5, 1997, now Pat. No. 6,111,960.

(30) **Foreign Application Priority Data**

Nov. 7, 1997 (EP) 97203440

(51) **Int. Cl.**[7] **H03G 5/00**

(52) **U.S. Cl.** **381/98**; 381/61; 381/62; 381/63

(58) **Field of Search** 381/98, 99, 100, 381/101, 102, 103, 104, 105, 106, 107, 108, 109, 61, 62, 63

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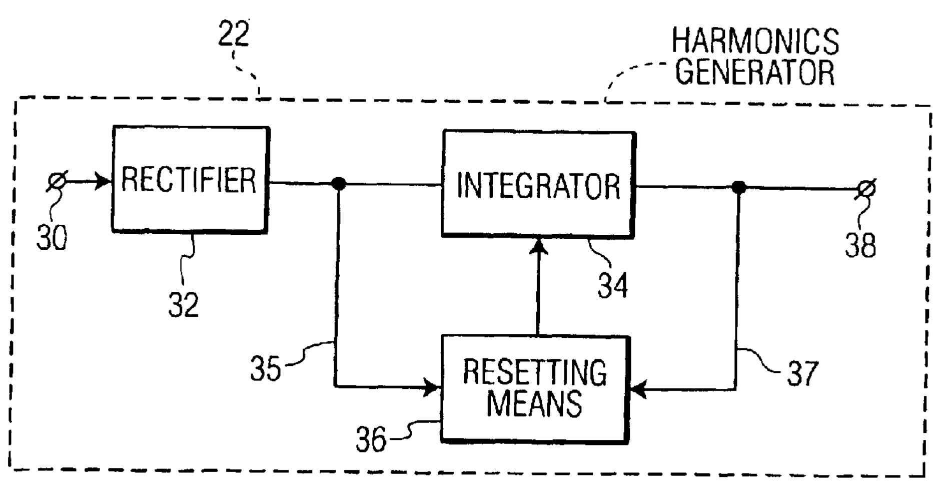
(74) *Attorney, Agent, or Firm*—Edward W. Goodman

(57) **ABSTRACT**

An audio system includes a circuit (**12**) for processing an audio signal, the circuit (**12**) having an input (**20**) for receiving the audio signal and an output (**26**) for supplying an output signal. The circuit (**12**) further includes a harmonics generator (**22**) coupled to the input (**20**) for generating harmonics of the audio signal and an adding circuit (**24**) coupled to the input (**20**) as well as to the harmonics generator (**22**) for supplying a sum of the audio signal and the generated harmonics to the output (**26**). The harmonics generator (**22**) includes an integrator (**34**) for integrating the audio signal, and, coupled thereto, a resetting circuit (**36**) for resetting the integrator (**34**) at resetting times.

8 Claims, 5 Drawing Sheets



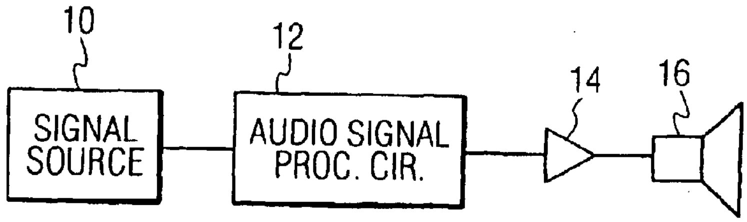


FIG. 1

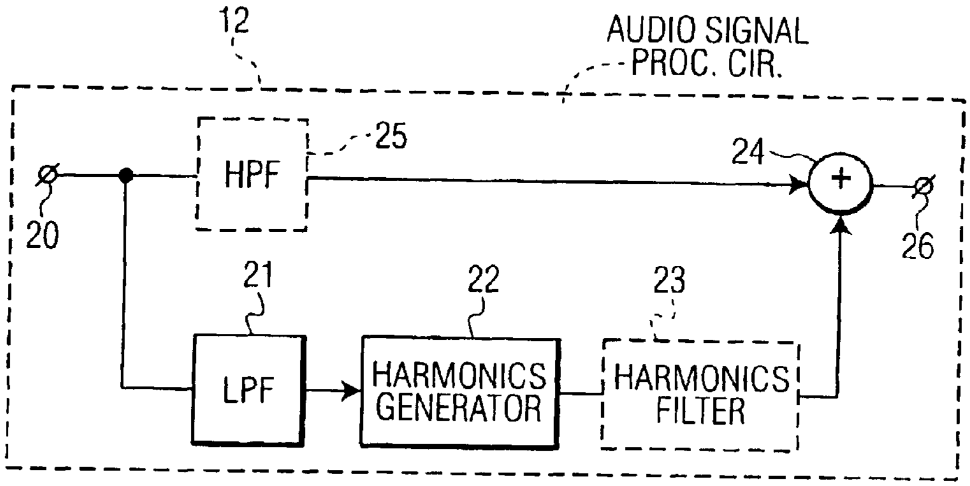


FIG. 2

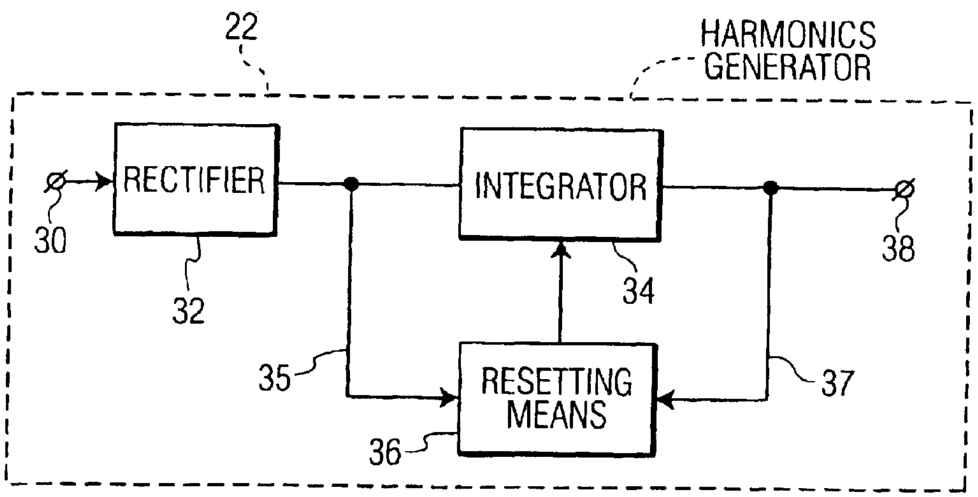


FIG. 3

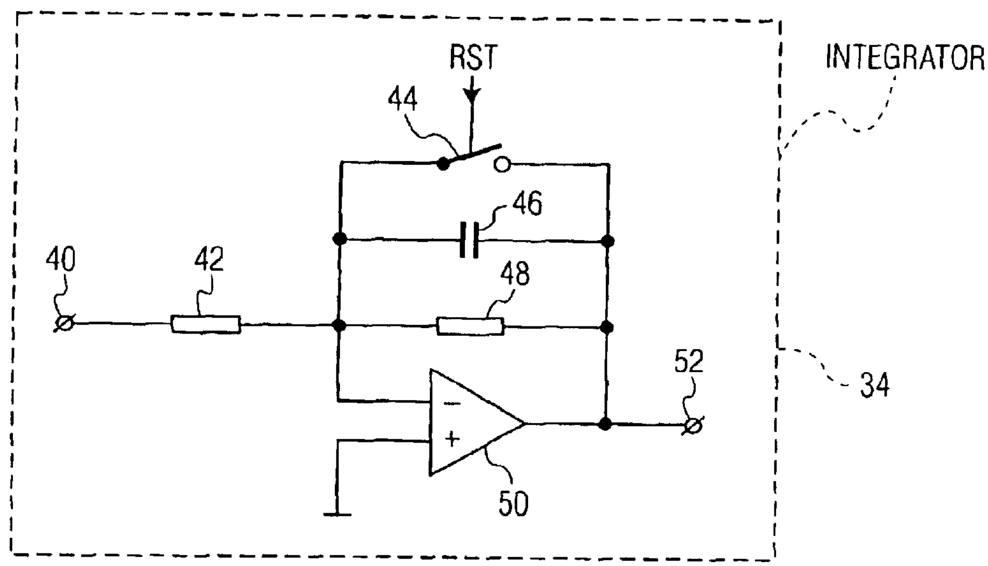

INTEGRATOR
RST
44
46
40
42
48
52
34
50

FIG. 4

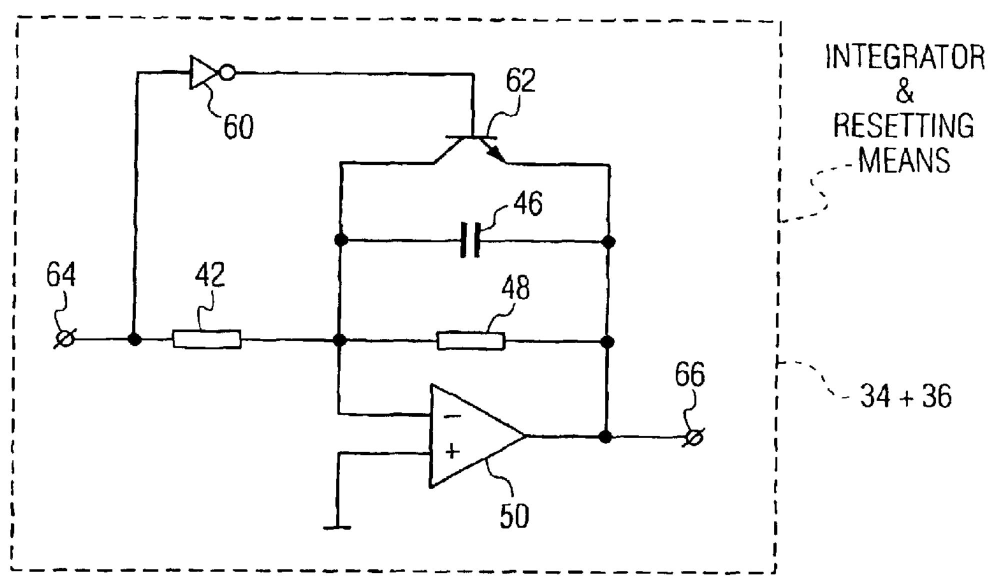

INTEGRATOR
&
RESETTING
MEANS
60
62
46
64
42
48
66
34 + 36
50

FIG. 5

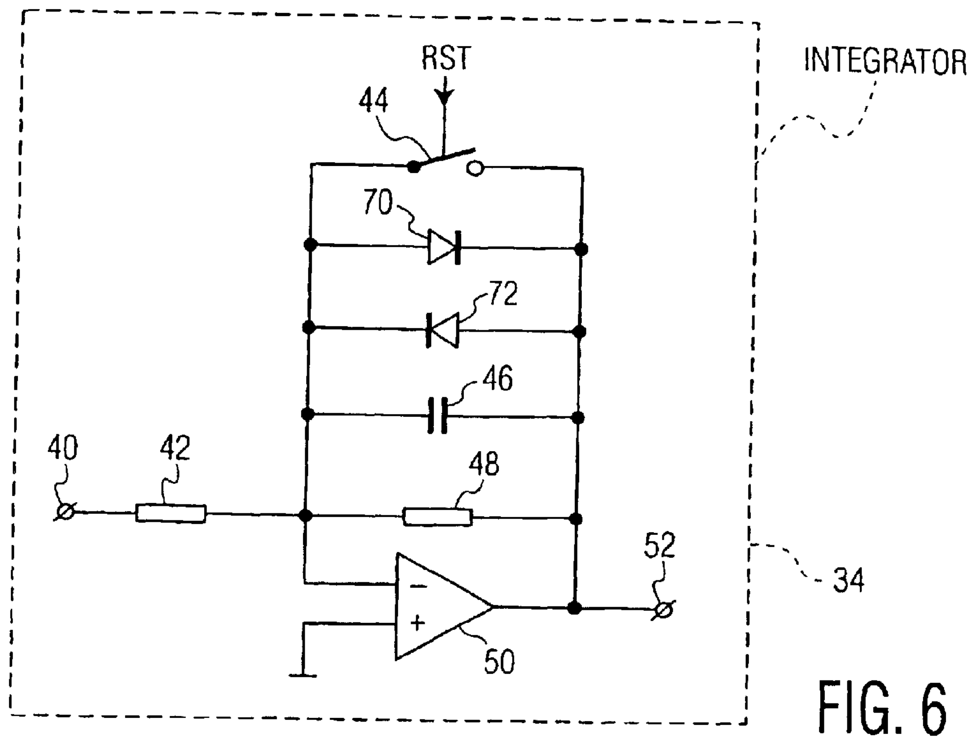

RST
INTEGRATOR
44
70
72
46
40
42
48
52
34
50

FIG. 6

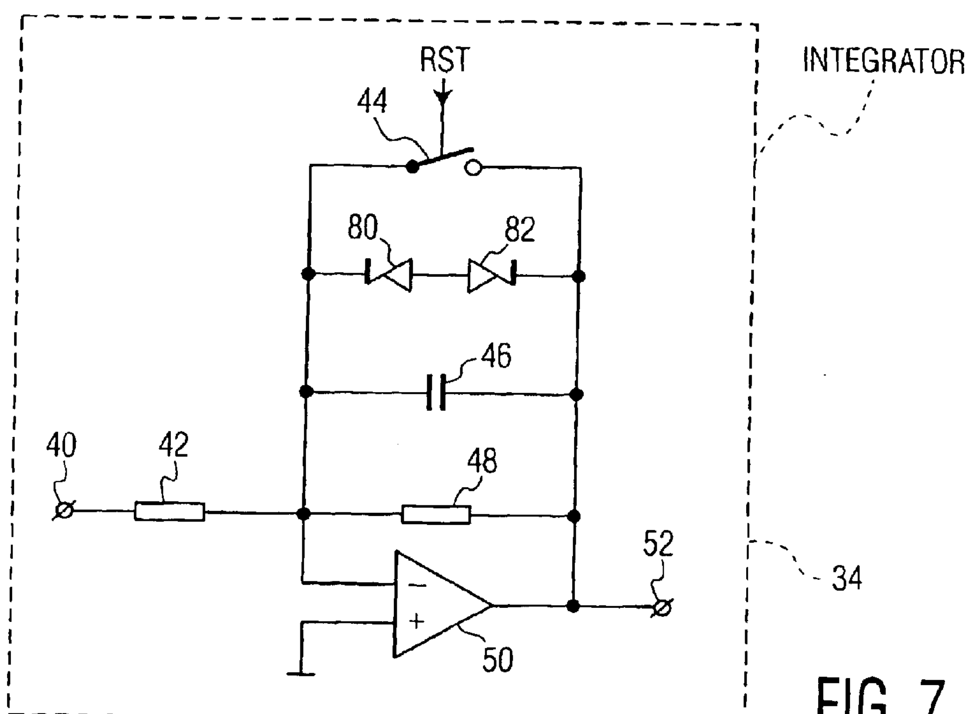

RST
INTEGRATOR
44
80
82
46
40
42
48
52
34
50

FIG. 7

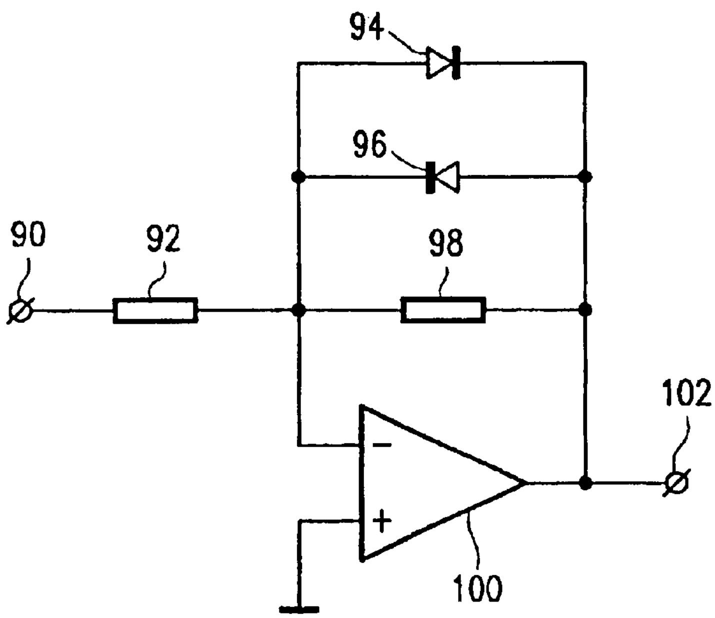


FIG. 8

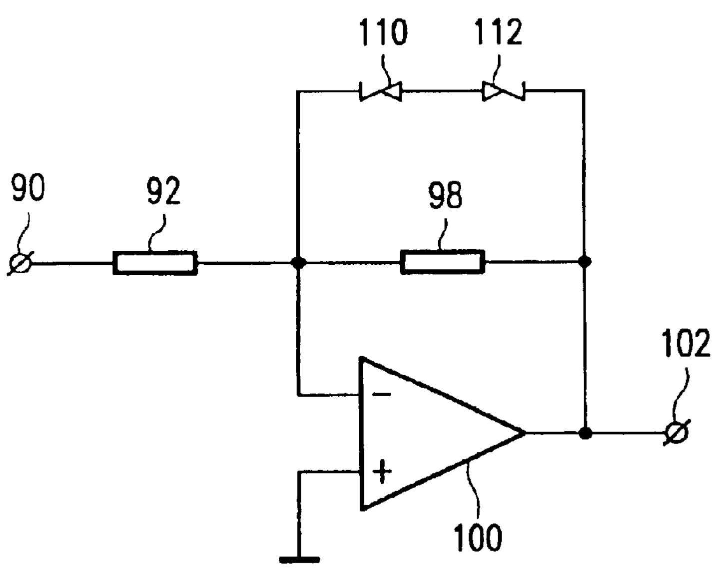


FIG. 9

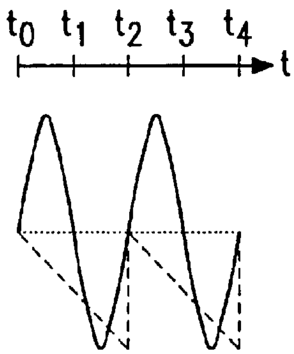


FIG. 10a

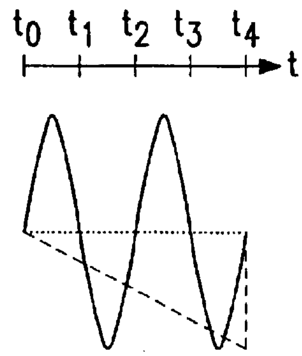


FIG. 10b

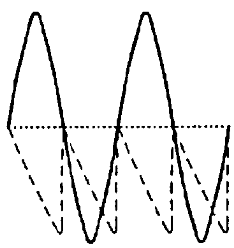


FIG. 10c

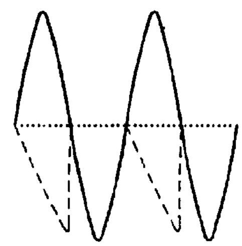


FIG. 10d

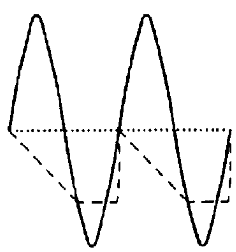


FIG. 10e

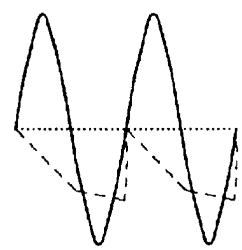


FIG. 10f

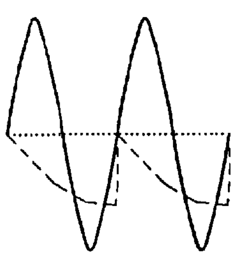


FIG. 10g

AUDIO SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of U.S. patent application Ser. No. 08/851,302, filed May 5, 1997, now U.S. Pat. No. 6,111,960.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to an audio system comprising a circuit for processing an audio signal, whereby the circuit comprises an input for receiving the audio signal and an output for supplying an output signal, a harmonics generator coupled to the input for generating harmonics of the audio signal, and adding means coupled to the input as well as to the harmonics generator for supplying a sum of the audio signal and the generated harmonics to the output.

The invention further relates to a circuit for processing an audio signal, a harmonics generator and a method for processing an audio signal.

2. Description of the Related Art

An audio system according to the preamble is known from European Patent Application EP-A 546 619. Since the invention of the electrodynamic loudspeaker, there has been a need for greater acoustical output, especially at low frequencies. Often, however, for instance, in television sets or portable audio sets, this acoustical output is severely limited by the small size of the loudspeakers. It is known that this dilemma can be solved by using a psychoacoustic phenomenon often referred to as virtual pitch or missing fundamental, which evokes the illusion of a higher bass-response, while the loudspeaker does not radiate more power at those low frequencies. This illusion can be created by replacing low-frequency tones, which are present in the audio signal but cannot be reproduced by a small loudspeaker, by harmonics of these tones. The harmonics now represent the low-frequency tones.

In the known audio system, a low-frequency band of an audio signal is selected and supplied to a harmonics generator for generating harmonics of the selected signal. The generated harmonics are thereafter added to the audio signal. In this way, the low-frequency perception of the audio signal is improved. In the known audio system, a full-wave rectifier is used as the harmonics generator, which generates only even harmonics. A drawback of the full-wave rectifier is that the amplitude of the generated harmonics decreases rapidly with the number of the harmonic, e.g., with respect to the second harmonic, the amplitudes of the fourth, sixth and eighth harmonics are, respectively, 14 dB, 21 dB and 26 dB lower. Because of this reduction in amplitude of the generated harmonics, the virtual pitch effect cannot be fully exploited in the known audio system.

SUMMARY OF THE INVENTION

An object of the invention is to provide an audio system, wherein the harmonics generator is capable of generating harmonics, the amplitudes of which are substantially equal to each other. This object is achieved in the audio system according to the invention, which is characterized in that the harmonics generator comprises an integrator for integrating the audio signal, and, coupled thereto, resetting means for resetting the integrator at resetting times.

By integrating the audio signal and resetting the integrated signal at resetting times, a non-symmetrical waveform is obtained which comprises both odd and even harmonics, whereby the amplitude of the generated harmonics decreases relatively slowly with the number of the harmonic. Consequently, in the audio system according to the invention, there is a relatively strong virtual pitch effect. Furthermore, because the amplitude of the generated harmonics is proportional to the amplitude of the audio signal, no annoying distortions in the output signal are introduced by the harmonics generator.

An embodiment of the audio system according to the invention is characterized in that the resetting means is embodied so as to periodically reset the integrator according to a reset period. By virtue of this measure, the generation of harmonics is repeated periodically, thus providing a constant stream of harmonics in the output signal.

A further embodiment of the audio system according to the invention is characterized in that the resetting means is embodied so as to determine the reset period in dependence on the period of the audio signal. This is a simple embodiment of the audio system according to the invention.

A further embodiment of the audio system according to the invention is characterized in that the resetting means is embodied so as to reset the integrator during at least a part of the reset period. By virtue of this measure, it is possible to prevent certain parts of the audio signal, for example, those parts where the amplitude of the audio signal is negative, from being integrated.

A further embodiment of the audio system according to the invention is characterized in that the resetting means is embodied so as to reset the integrator when the audio signal crosses a threshold value. By virtue thereof, integration of those parts of the audio signal which exceed a certain threshold value can be prevented.

A further embodiment of the audio system according to the invention is characterized in that the harmonics generator further comprises a rectifier for rectifying the audio signal, whereby the rectifier is coupled to the integrator so that the rectified signal is integrated by the integrator. By virtue of this measure, also the negative parts of the audio signal contribute to the amplitude of the generated harmonics.

Some low-frequency tones, which are reproduced by the audio system according to the invention, are perceived by human beings as having a higher loudness than the loudness of the corresponding low-frequency tones which are present in the audio signal. In order to compensate for this undesired artefact, a further embodiment of the audio system according to the invention is characterized in that the integrator is embodied so as to limit the amplitude of the integrated signal. In this way, the perceived loudness of low-frequency tones can be controlled, preferably, in such a manner that the perceived loudness is substantially equal to the original loudness.

A further embodiment of the audio system according to the invention is characterized in that the integrator is embodied so as to stop the integration in dependence on the amplitude of the integrated signal. This is a simple and effective embodiment for limiting the amplitude of the integrated signal and thus the perceived loudness of low-frequency tones.

A further embodiment of the audio system according to the invention is characterized in that the integrator is embodied so as to adapt an integration time-constant in dependence on the amplitude or the frequency of the integrated signal. By virtue of this measure, the amplitude of the integrated signal can be limited gradually, enabling a smooth control of the perceived loudness of low-frequency tones.

BRIEF DESCRIPTION OF THE DRAWINGS

The above object and features of the present invention will be more apparent from the following description of the preferred embodiments with reference to the drawings, wherein:

FIG. **1** shows a block diagram of an audio system according to the invention;

FIG. **2** shows a block diagram of a circuit for processing an audio signal according to the invention;

FIG. **3** shows a block diagram of a harmonics generator according to the invention;

FIG. **4** shows a first embodiment of an integrator which can be used in the present invention;

FIG. **5** shows a circuit for use in the present invention, in which an integrator and a resetting means are combined;

FIGS. **6** and **7** show second and third embodiments, respectively, of an integrator for use in the present invention;

FIGS. **8** and **9** show first and second embodiments, respectively, of a limiter which can be used in the present invention in combination with an integrator as shown, for example, in FIGS. **4** and **5**; and

FIGS. **10***a*–**10***g* show diagrams of various waveforms generated in response to a sinusoidal input signal applied to a harmonics generator according to the invention.

In the Figures, identical parts are provided with the same reference numbers.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** shows a block diagram of an audio system according to the invention. The audio system comprises a signal source **10**, which is coupled, via a circuit **12** and an amplifier **14**, respectively, to a loudspeaker **16**. The signal source **10** may derive its signal from a CD, a cassette or a received signal or any other audio source. The circuit **12** processes the audio signal supplied by the signal source **10** in such a way that low-frequency tones, which are present in the audio signal but cannot be reproduced by the loudspeaker **16** because of its limited size, are replaced by harmonics of these tones. These harmonics, which can be reproduced by the loudspeaker **16**, evoke the illusion of a higher bass response. This psychoacoustical phenomenon is often referred to as virtual pitch or missing fundamental. The audio signal, which is processed by the circuit **12**, is thereafter amplified by the amplifier **14**. This amplified signal is then reproduced by the loudspeaker **16**.

FIG. **2** shows a block diagram of a circuit **12** for processing an audio signal according to the invention. The circuit **12** comprises an input **20** for receiving an audio signal and an output **26** for supplying an output signal. The circuit **12** further comprises a harmonics generator **22** coupled to the input **20**, and adding means **24**, coupled to the input **20** and the harmonics generator **22**, for supplying the sum of the audio signal and the output signal of the harmonics generator **22** to the output **26**.

In the circuit **12** for processing an audio signal, a first filter **21** is inserted between the input **20** and the harmonics generator **22**. Preferably, this first filter **21** is a low-pass filter so as to pass those low-frequency components in the audio signal which cannot be reproduced by the loudspeaker **16**, while, at the same time, spurious dc components in the audio signal are blocked. It is also possible to insert a second filter **23** in the circuit **12** between the harmonics generator **22** and the adding means **24**. By means of this second filter **23**, the number of harmonics which are reproduced by the loudspeaker **16** can be controlled. Furthermore, a third filter **25** can be inserted in the circuit **12** between the input **20** and the adding means **24**. Preferably, this third filter **25** may be a high-pass filter for blocking those low-frequency components in the audio signal which cannot be reproduced by the loudspeaker, thus preventing an overload of the loudspeaker **16**.

FIG. **3** shows a block diagram of a harmonics generator **22** according to the invention. The harmonics generator **22** comprises an input **30** for receiving an audio signal and an output **38** for supplying an output signal. The harmonics generator **22** further comprises an integrator **34** and, coupled thereto, a resetting means **36**. The integrator **34** integrates the audio signal received by the input **30** and supplies the integrated signal to the output **38**. The resetting means **36** is embodied so as to reset the integrator **34** at resetting times. In this way, the output signal comprises both odd and even harmonics, whereby the amplitudes of these harmonics are substantially equal to each other. Furthermore, because the amplitude of the generated harmonics is proportional to the amplitude of the audio signal, no annoying distortions are introduced by the harmonics generator **22**.

The resetting times can be determined by the resetting means **36** in a number of different ways. The resetting means **36** can determine the resetting times in dependence on some properties of the audio signal, for instance, the period, the amplitude or the zero crossings. It is also possible that the resetting means **36** determines the resetting times in dependence on similar properties of the output signal. Furthermore, the resetting means **36** may determine the resetting times in dependence on both the audio signal and the output signal. It may be clear that in a specific embodiment of the harmonics generator **22** according to the invention, only one or both of the connections **35** and **37** are present.

The harmonics generator **22** may further comprise a rectifier **32**, which rectifies the audio signal received by the input **30**.

FIG. **4** shows a first embodiment of an integrator **34** which can be used in the present invention. The integrator **34** comprises an input **40** for receiving an input signal and an output **52** for supplying an output signal. The integrator **34** further comprises an operational amplifier **50**, the positive input of which is grounded. A resistor **48**, a capacitor **46** and a switch **44** are placed in parallel with each other and couple the negative input of the operational amplifier **50** to its output. This negative input of the operational amplifier **50** is also coupled, via a resistor **42**, to the input **40**. The output of the operational amplifier **50** is coupled to the output **52** of the integrator **34**. The switch **44** is controlled by the reset signal RST, which is generated by the resetting means **36** in such a way that the switch **44** is closed at resetting times.

It will be clear to a person skilled in the art that the input signal received at the input **40** is integrated by this embodiment of the integrator **34**, whereby the integrated signal is supplied to the output **52**. The integrator is reset, i.e., the capacitor **46** is discharged and the output signal is reset to zero, when the switch **44** is closed.

FIG. **5** shows a circuit for use in the present invention, in which an integrator **34** and a resetting means **36** are combined. This circuit comprises an input **64** for receiving an input signal and an output **66** for supplying an output signal. The circuit further comprises the elements of FIG. **4** which are needed for the integration of the input signal, i.e., the resistors **42** and **48**, the operational amplifier **50** and the capacitor **46**. The switch **44** is implemented by means of the transistor **62**. Because the base of this transistor **62** is coupled via an inverter **60** to the input **64**, the transistor **62** conducts (i.e., the switch **44** is closed and the integrator is reset) when the input signal is negative. On the other hand, when the input signal is positive, the transistor **62** does not conduct, i.e., the switch **44** is open.

Some low-frequency tones, which are reproduced by the audio system according to the invention, are perceived by human beings as having a higher loudness than the loudness of the corresponding low-frequency tones which are present in the audio signal. In order to compensate for this undesired artefact, the integrator **34** can be embodied so as to limit the amplitude of the integrated signal. In this way, the perceived loudness of low-frequency tones can be controlled, preferably in such a manner that the perceived loudness is substantially equal to the original loudness.

FIGS. **8** and **9** show first and second embodiments, respectively, of a limiter which can be used to limit the range of the output signal of an integrator **34** as shown, for example, in FIGS. **4** and **5**. In FIGS. **8** and **9**, the limiter comprises an inverting amplifier, which is comprised of an input **90**, an output **102**, an operational amplifier **100** and two resistors **92** and **98**. The absolute value of the voltage gain of this inverting amplifier is equal to the resistance of the resistor **98** divided by the resistance of the resistor **92**. In the limiter of FIG. **8**, two diodes **94** and **96**, which are placed in parallel with the resistor **98**, prevent an output signal of the inverting amplifier from exceeding certain voltage limits. Because the positive input of the operational amplifier **100** is grounded, the voltage at the negative input is also zero (virtual ground). Thus, diode **94** conducts when the output signal is negative, i.e., when the input signal, which is received by the input **90**, is positive. In the same way, diode **96** conducts when the output signal is positive, i.e., when the input signal is negative. In this way, when using silicon diodes, the range of the output signal is limited between, approximately, –0.6 and +0.6 volts.

In the limiter of FIG. **9**, the task of preventing the output signal of the inverting amplifier from exceeding certain voltage limits is performed by two zener diodes **110** and **112**. Here, the zener diode **110** conducts when the output signal is positive, and the zener diode **112** conducts when the output signal is negative. In this way, the range of the output signal is limited between approximately the inverted zener voltage of the zener diode **110** and the zener voltage of the zener diode **112**.

The limiters as shown in FIGS. **8** and **9** can be coupled to the integrator **34** as shown, for example, in FIG. **4**. This coupling may, for instance, be effected in such a way that the output **52** of the integrator **34** is connected to the input **90** of the limiter, thus providing for a limitation of the output signal of the integrator **34**. It is also possible to couple the output **102** of the limiter to the input **40** of the integrator **34**, thus providing for a limitation of the input signal of the integrator **34**. Furthermore, it is possible to combine the function of the limiter with that of the integrator **34**. Two examples of such a combination are shown in FIGS. **6** and **7**. FIG. **6** shows the combination of the limiter of FIG. **8** with the integrator **34** as shown in FIG. **4**. The combination of the limiter of FIG. **9** with the integrator **34** as shown in FIG. **4** is depicted in FIG. **7**.

The integrator **34** as shown, for example, in FIG. **4** may also be embodied so as to adapt an integration time-constant in dependence on the amplitude of the integrated signal. By virtue of this measure, the amplitude of the integrated signal can be limited gradually, thus enabling a smooth control of the perceived loudness of low-frequency tones. This adaptation of the integration time-constant can be achieved by altering the resistance of the resistor **42** and/or the capacitance of the capacitor **46**. The effective resistance of the resistor **42** can be changed, for instance, by switching one or more resistors in series or parallel with the resistor **42**. The effective capacitance of the capacitor **46** can be changed, for instance, by switching one or more capacitors in series or in parallel with the capacitor **46**.

FIGS. **10***a*—**10***g* show styled diagrams of various waveforms generated in response to a sinusoidal input signal applied to an harmonics generator **22** according to the invention. In these diagrams, the input signal is indicated by a straight line and the generated waveform is indicated by means of a dashed line. The waveform in FIG. **10***a* can be generated by the harmonics generator **22** according to the invention, in which the input signal is rectified before being integrated, whereby the integrator **34** is reset by the resetting means **36** at the end of each period of the input signal. The waveforms in FIGS. **10***b* and **10***c* can be generated by the harmonics generator **22** in a similar fashion, whereby, for the waveform in FIG. **10***b*, the integrator **34** is reset at the end of each second period of the input signal, and for the waveform in FIG. **10***c*, the integrator **34** is reset at each zero crossing of the input signal. The waveform in FIG. **10***d* can be generated by the harmonics generator **22**, whereby the harmonics generator **22** comprises the combination of the integrator **34** and the resetting means **36** as depicted in FIG. **5**. In this case, the harmonics generator **22** does not comprise the rectifier **22**.

The waveforms in FIGS. **10***e*—**10***g* can be generated by the harmonics generator **22** according to the invention in a similar fashion as described above for the waveform in FIG. **10***a*. The waveform in FIG. **10***e* is generated by the harmonics generator **22**, which is embodied so as to stop the integration in dependence on the amplitude of the integrated signal. Here, the harmonics generator **22** may comprise an integrator **34** as shown in FIGS. **6** and **7**, or an integrator **34** as depicted in FIG. **4** in combination with a limiter circuit as shown, for example, in FIGS. **8** and **9**.

The waveforms in FIG. **10***f* and log illustrate the adaptation of an integration time-constant by the integrator **34**. In order to generate the waveform in FIG. **10***f*, the integration time-constant of the integrator **34** is adapted once during each period of the input signal, whereby this adaptation depends on, for example, the amplitude or the frequency of the integrated signal. The waveform in FIG. **10***g* may be generated in a similar fashion, whereby the integrator **34** is adapted twice during each period of the input signal. Of course, it is also possible to arrange the integrator **34** in such a way that more than two adaptations of the integration time-constant are supported.

It will be obvious to those having ordinary skill in the art that many changes may be made to the above-described invention without departing from the underlying principles thereof. For example, the signal processing performed in the entities according to the invention may also be performed by a dedicated integrated circuit or in software running on a programmable processor. Furthermore, in the integrator **34** as shown, for example, in FIG. **4**, the resistor **48** may be omitted. A desired limitation of the amplitude of the output signal of the harmonics generator **22** can also be achieved by means of a multiplication of the input or output signal with a certain multiplication factor.

What is claimed is:

1. An audio system comprising a circuit for processing an audio signal, said audio signal processing circuit comprising:

an input for receiving the audio signal and an output for supplying an output signal;

filtering means coupled to said input for passing low-frequency components of said audio signal to form a filtered audio signal;

a harmonics generator coupled to the filtering means for generating harmonics of the filtered audio signal; and

adding means coupled to the input as well as to the harmonics generator for supplying a sum of the audio signal and the generated harmonics to the output, characterized in that the harmonics generator comprises:

an input for receiving the filtered audio signal;

rectifying means coupled to the input for rectifying the filtered audio signal;

an integrator coupled to the rectifying means for integrating the rectified filtered audio signal; and

resetting means coupled to the integrator for resetting the integrator at resetting times,

characterized in that the integrator comprises means for limiting an amplitude of the integrated signal, and the integrator adapts an integration time-constant in dependence on a frequency of the integrated signal.

2. The audio system as claimed in claim 1, characterized in that the resetting means periodically resets the integrator according to a reset period.

3. The audio system as claimed in claim 2, characterized in that the resetting means comprises means for determining the reset period in dependence on a period of the audio signal.

4. The audio system as claimed in claim 2, characterized in that the resetting means resets the integrator during at least a part of the reset period.

5. The audio system as claimed in claim 1, characterized in that the resetting means comprises means for detecting when the audio signal crosses a threshold value, said resetting means resetting the integrator when said detecting means detects that the audio signal crosses the threshold value.

6. A circuit for processing an audio signal, said audio signal processing circuit comprising:

an input for receiving the audio signal and an output for supplying an output signal;

filtering means coupled to said input for passing low-frequency components of said audio signal to form a filtered audio signal;

a harmonics generator coupled to the filtering means for generating harmonics of the filtered audio signal; and

adding means coupled to the input as well as to the harmonics generator for supplying a sum of the audio signal and the generated harmonics to the output,

characterized in that the harmonics generator comprises:

an input for receiving the filtered audio signal;

rectifying means coupled to the harmonics generator input for rectifying the filtered audio signal;

an integrator coupled to the rectifying means for integrating the rectified filtered audio signal; and

resetting means coupled to the integrator for resetting the integrator at resetting times,

wherein the integrator comprises means for limiting an amplitude of the integrated signal, and the integrator adapts an integration time-constant in dependence on a frequency of the integrated signal.

7. A harmonics generator comprising:

an input for receiving an audio signal;

rectifying means coupled to the input for rectifying the audio signal;

an integrator coupled to the rectifying means for integrating the rectified audio signal; and

resetting means coupled to the integrator for resetting the integrator at resetting times,

wherein the integrator comprises means for limiting an amplitude of the integrated signal, and the integrator adapts an integration time-constant in dependence on a frequency of the integrated signal.

8. A method for processing an audio signal, said method comprising the steps:

filtering said audio signal for passing low-frequency components of said audio signal to form a filtered audio signal;

generating harmonics of the filtered audio signal; and

forming a sum of the audio signal and the generated harmonics,

characterized in that the step of generating harmonics comprises:

rectifying the filtered audio signal;

integrating the rectified filtered audio signal;

resetting the integration at resetting times;

limiting an amplitude of the integrated signal; and

adapting an integration time-constant in dependence on a frequency of the integrated signal.

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