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(71) Applicant: **Oticon A/S**
2765 Smørum (DK)

(72) Inventor: **Pontoppidan, Niels Henrik**
DK-2765 Smørum (DK)

(74) Representative: **William Demant**
Oticon A/S
Kongebakken 9
2765 Smørum (DK)

(54) AUDIO DEVICE WITH MEMS SPEAKER

(57) The invention relates to an audio device that comprises an electro-acoustic transducer unit that comprises a multitude of micro-electro-mechanical speaker elements. The audio device further comprises a speaker control that is operationally connected to the micro-electro-mechanical speaker elements and configured to drive the micro-electro-mechanical speaker elements so as to reproduce a desired audio signal, each micro-electro-mechanical speaker element being configured to perform a low-to-high state transition and a high-to-low state transition.

The speaker control unit is configured to drive the micro-electro-mechanical speaker elements so that the micro-electro-mechanical speaker elements can further perform an unattenuated low-to-high state transition leading to a relatively higher sound pressure level and an attenuated low-to-high state transition state transition leading to a relatively lower sound pressure level as well as an unattenuated high-to-low state transition leading to a relatively higher sound pressure level and an attenuated high-to-low state leading to a relatively lower sound pressure level. The speaker control unit is further configured to drive the micro-electro-mechanical speaker elements to perform either an unattenuated low-to-high state transition or an attenuated low-to-high state transition state transition, respectively, and an unattenuated high-to-low state transition or an attenuated high-to-low state, respectively, depending on a sound pressure level required to reproduce the desired audio signal.

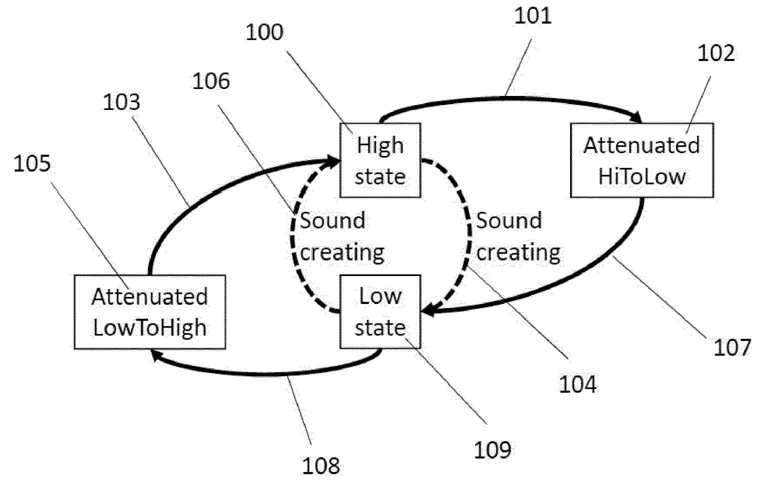

Fig. 6

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Description

TECHNICAL FIELD

[0001] The invention relates to an audio device that has a MEMS loudspeaker unit array for generating an acoustic output signal

BACKGROUND

[0002] MEMS loudspeaker unit arrays are inter alia described in WO 2007/135679, WO 2015/033346 A1 or WO 2017/039905 A1.

[0003] MEMS loudspeakers are electro-acoustic transducers that convert an electric signal, i.e. an electric audio signal into an acoustic signal, i.e. an acoustic signal that can be perceived as sound. A MEMS loudspeaker comprises a plurality of MEMS loudspeaker units. The MEMS loudspeaker is a micro-electro-mechanical system (MEMS) wherein each of the plurality of MEMS loudspeaker units comprises a movable diaphragm with a very small surface area and a small travel. Each diaphragm can be moved between a retracted, low state and forwarded, high state. Typically each diaphragm can be controlled individually and will move between the two states (high state to low state and vice versa) with a predetermined speed. The speed can be high and a number of diaphragms can move simultaneously to thus generate elementary waves that can interfere and thus create a sound wave similar to the sound wave generated by a conventional coil and cone loudspeaker.

[0004] Because the individual MEMS loudspeaker units (the individual diaphragms) can be digitally controlled and only can assume a low state and a high state, these types of MEMS loudspeakers are also referred to as digital loudspeakers.

[0005] Small size is an advantage of MEMS loudspeakers. The inventors found, however, that the acoustic sound produced by prior art MEMS loudspeakers could be improved.

SUMMARY

[0006] It is therefore an object of the invention to provide an audio device that comprises a MEMS loudspeaker unit array and that provides an improved acoustic output sound.

[0007] The term "MEMS loudspeaker unit" is used for a single MEMS element of the MEMS system. An array of a plurality of MEMS loudspeaker units forms a MEMS loudspeaker.

[0008] According to the invention, the object is achieved by an audio device that comprises an electro-acoustic transducer unit that comprises a multitude of micro-electro-mechanical speaker elements - also referred to as MEMS loudspeaker units hereinafter. The audio device further comprises a speaker control that is operationally connected to the micro-electro-mechanical speaker elements and configured to drive the micro-electro-mechanical speaker elements so as to reproduce a desired audio signal, each micro-electro-mechanical speaker element being configured to perform a low-to-high state transition and a high-to-low state transition.

[0009] The speaker control unit is configured to drive the micro-electro-mechanical speaker elements so that the micro-electro-mechanical speaker elements can further perform an unattenuated low-to-high state transition leading to a relatively higher sound pressure level and an attenuated low-to-high state transition state transition leading to a relatively lower sound pressure level as well as an unattenuated high-to-low state transition leading to a relatively higher sound pressure level and an attenuated high-to-low state leading to a relatively lower sound pressure level. The speaker control unit is further configured to drive the micro-electro-mechanical speaker elements to perform either an unattenuated low-to-high state transition or an attenuated low-to-high state transition, respectively, and an unattenuated high-to-low state transition or an attenuated high-to-low state, respectively, depending on a sound pressure level required to reproduce the desired audio signal.

[0010] Accordingly, each micro-electro-mechanical speaker element can perform two different state transitions thus being able not only to always produce the full sound level but also being able to produce an intermediate sound level when actuated.

[0011] In a preferred embodiment, the attenuated state transitions are achieved by driving the micro-electro-mechanical speaker elements so they travel with a lower speed between the high state and the low state or vice versa, respectively. For instance, the speed of the micro-electro-mechanical speaker elements may be controlled by a frequency content of a control signal which drives the micro-electro-mechanical speaker elements. In particular, low-pass filtering of the driving control signal with a lower cut-off frequency can lower the speed. Thus, an embodiment can involve two capacitive low pass networks with low and high cut-off frequency and besides from that use a design similar to that disclosed in WO 2015/033346 and WO 2007/135679 mentioned above.

[0012] Accordingly it is preferred if the speaker control unit is configured to drive the micro-electro-mechanical speaker elements so that they can travel with two different speeds between the high state and the low state or vice versa, respectively, a high speed resulting in a fast state change and thus in an unattenuated low-to-high state transition or a unattenuated high-to-low state transition, respectively, whereas a lower travel speed results in a slow state change and thus in an attenuated low-to-high state transition or a attenuated high-to-low state transition, respectively.

[0013] Alternatively or in addition to providing different travelling speeds, the micro-electro-mechanical speaker elements can be configured or driven so that they can adopt an intermediate state between the low state and the high state, i.e. travelling only half-way when actuated. Accordingly, an attenuated state transition can be achieved by driving a micro-electro-mechanical speaker element so that it travels to or from an intermediate state.

[0014] Another alternative that can be combined with the previous alternative is to provide micro-electro-mechanical speaker elements with variable acoustic impedance, i.e. by altering a surface of a micro-electro-mechanical speaker element so that the micro-electro-mechanical speaker element moves or compresses, respectively, less air when travelling from its low state to its high state or vice versa. The effect is similar to actuating only one instead of two adjacent micro-electro-mechanical speaker elements. For instance, at least some micro-electro-mechanical speaker elements can be made switchable between a high acoustical impedance state and a low acoustical impedance state so that an unattenuated low-to-high state transition and an unattenuated high-to-low state transition is achieved in the micro-electro-mechanical speaker element's high acoustical impedance state whereas an attenuated low-to-high state transition and an attenuated high-to-low state transition is achieved in the micro-electro-mechanical speaker element's low acoustical impedance state.

[0015] Accordingly, in one preferred embodiment, at least some micro-electro-mechanical speaker elements are switchable between a high acoustical impedance state and a low acoustical impedance state so that an unattenuated low-to-high state transition and an unattenuated high-to-low state transition is achieved in the micro-electro-mechanical speaker element's high acoustical impedance state whereas an attenuated low-to-high state transition and an attenuated high-to-low state transition is achieved in the micro-electro-mechanical speaker element's low acoustical impedance state.

[0016] In order to provide different acoustic impedances, the micro-electro-mechanical speaker elements may comprise a diaphragm with a surface area that can be varied to impart different acoustic impedances.

[0017] In a preferred embodiment, the diaphragm may comprise two layers with holes. The two layers are configured to change their respective rotational position wherein in one rotational position the holes of both layers are aligned, resulting in a diaphragm with a lower effective surface area and thus a lower acoustic impedance, while in another rotation position, the holes of the layers are disaligned resulting in a diaphragm without holes and thus a large effective surface and a higher acoustic impedance.

[0018] Speaker control unit preferably comprises a micro-electro-mechanical speaker element scheduler that is configured to transform an output audio signal into a multichannel control signal that represents a sequence of state changes for each micro-electro-mechanical speaker element of the multitude of micro-electro-mechanical speaker elements.

[0019] Preferably, the audio device further comprises

- a front end for receiving a time-domain input audio signal,
- an analyzing filter bank for analyzing the received time-domain input audio signal and generating a time/frequency-domain audio signal,
- a processing unit for processing the time/frequency-domain audio signal, and
- a synthesis filter bank for generating the output audio signal and a level signal from the time/frequency-domain audio signal and feeding the output audio signal and a level signal to the micro-electro-mechanical speaker element scheduler.

[0020] The micro-electro-mechanical speaker element scheduler may comprise:

- a look ahead unit,
- a spectrum unit,
- a masking model unit, and
- a sequencer.

BRIEF DESCRIPTION OF DRAWINGS

[0021] The aspects of the disclosure may be best understood from the following detailed description taken in conjunction with the accompanying figures. The figures are schematic and simplified for clarity, and they just show details to improve the understanding of the claims, while other details are left out. Throughout, the same reference numerals are used for identical or corresponding parts. The individual features of each aspect may each be combined with any or all features of the other aspects. These and other aspects, features and/or technical effect will be apparent from and elucidated with reference to the illustrations described hereinafter in which:

Figure 1:	shows an audio device that has a MEMS loudspeaker unit array;
Figures 2 a), b) and c)	illustrate an array of binary MEMS loudspeaker units;
Figure 3 a), b) and c)	illustrate how an acoustic sound can be shaped by controlling the MEMS loudspeaker units according to audio signal to be reproduced as acoustic signal;
Figure 4:	illustrates that the prior art MEMS units array's ability to generate low frequency sounds is limited;
Figure 5:	is a schematic block diagram showing further implementation details of speaker control unit according to an exemplary embodiment of the invention;
Figure 6:	is a state diagram for the optimized MEMS units;
Figure 7:	is a schematic block diagram showing further implementation details of an audio device according to an exemplary embodiment of the invention;
Figure 8:	illustrates a MEMS loudspeaker unit array with MEMS loudspeaker units that can adopt three states; and
Figures 9 and 10	illustrate embodiments of a MEMS loudspeaker unit that has a variable acoustic impedance.

DETAILED DESCRIPTION

[0022] The detailed description set forth below in connection with the appended drawings is intended as a description of various configurations. The detailed description includes specific details for the purpose of providing a thorough understanding of various concepts. However, it will be apparent to those skilled in the art that these concepts may be practiced without these specific details. Several aspects of the apparatus and methods are described by various blocks, functional units, modules, components, circuits, steps, processes, algorithms, etc. (collectively referred to as "elements"). Depending upon particular application, design constraints or other reasons, these elements may be implemented using electronic hardware, computer program, or any combination thereof.

[0023] A hearing device may include a hearing aid that is adapted to improve or augment the hearing capability of a user by receiving an acoustic signal from a user's surroundings, generating a corresponding audio signal, possibly modifying the audio signal and providing the possibly modified audio signal as an audible signal to at least one of the user's ears. The "hearing device" may further refer to a device such as an earphone or a headset adapted to receive an audio signal electronically, possibly modifying the audio signal and providing the possibly modified audio signals as an audible signal to at least one of the user's ears. Such audible signals may be provided in the form of an acoustic signal radiated into the user's outer ear, or an acoustic signal transferred as mechanical vibrations to the user's inner ears through bone structure of the user's head and/or through parts of middle ear of the user or electric signals transferred directly or indirectly to cochlear nerve and/or to auditory cortex of the user.

[0024] The hearing device is adapted to be worn in any known way. This may include i) arranging a unit of the hearing device behind the ear with a tube leading air-borne acoustic signals or with a receiver/ loudspeaker arranged close to or in the ear canal such as in a Behind-the-Ear type hearing aid or a Receiver-in-the Ear type hearing aid, and/ or ii) arranging the hearing device entirely or partly in the pinna and/ or in the ear canal of the user such as in a In-the-Ear type hearing aid or In-the-Canal/ Completely-in-Canal type hearing aid, or iii) arranging a unit of the hearing device attached to a fixture implanted into the skull bone such as in Bone Anchored Hearing Aid or Cochlear Implant, or iv) arranging a unit of the hearing device as an entirely or partly implanted unit such as in Bone Anchored Hearing Aid or Cochlear Implant.

[0025] A hearing device may be part of a "hearing system", which refers to a system comprising one or two hearing devices, disclosed in present description, and a "binaural hearing system" refers to a system comprising two hearing devices where the devices are adapted to cooperatively provide audible signals to both of the user's ears. The hearing system or binaural hearing system may further include auxiliary device(s) that communicates with at least one hearing device, the auxiliary device affecting the operation of the hearing devices and/or benefitting from the functioning of the hearing devices. A wired or wireless communication link between the at least one hearing device and the auxiliary device is established that allows for exchanging information (e.g. control and status signals, possibly audio signals) between the at least one hearing device and the auxiliary device. Such auxiliary devices may include at least one of remote controls, remote microphones, audio gateway devices, mobile phones, public-address systems, car audio systems or music players or a combination thereof. The audio gateway is adapted to receive a multitude of audio signals such as from an entertainment device like a TV or a music player, a telephone apparatus like a mobile telephone or a computer, a PC. The audio gateway is further adapted to select and/or combine an appropriate one of the received audio signals (or combination of signals) for transmission to the at least one hearing device. The remote control is adapted to control functionality and operation of the at least one hearing devices. The function of the remote control may be implemented in a SmartPhone or other electronic device, the SmartPhone/ electronic device possibly running an application that controls functionality of the at least one hearing device.

[0026] In general, a hearing device includes i) an input unit such as a microphone for receiving an acoustic signal from a user's surroundings and providing a corresponding input audio signal, and/or ii) a receiving unit for electronically receiving an input audio signal. The hearing device further includes a signal processing unit for processing the input audio signal and an output unit for providing an audible signal to the user in dependence on the processed audio signal.

[0027] The input unit may include multiple input microphones, e.g. for providing direction-dependent audio signal processing. Such directional microphone system is adapted to enhance a target acoustic source among a multitude of acoustic sources in the user's environment. In one aspect, the directional system is adapted to detect (such as adaptively detect) from which direction a particular part of the microphone signal originates. This may be achieved by using conventionally known methods. The signal processing unit may include amplifier that is adapted to apply a frequency dependent gain to the input audio signal. The signal processing unit may further be adapted to provide other relevant functionality such as compression, noise reduction, etc. The output unit may include an output transducer such as a loudspeaker/ receiver for providing an air-borne acoustic signal transcutaneously or percutaneously to the skull bone or a vibrator for providing a structure-borne or liquid-borne acoustic signal. In some hearing devices, the output unit may include one or more output electrodes for providing the electric signals such as in a Cochlear Implant.

[0028] It should be appreciated that reference throughout this specification to "one embodiment" or "an embodiment" or "an aspect" or features included as "may" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the disclosure. Furthermore, the particular features, structures or characteristics may be combined as suitable in one or more embodiments of the disclosure. The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these aspects will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects.

[0029] The claims are not intended to be limited to the aspects shown herein, but is to be accorded the full scope consistent with the language of the claims, wherein reference to an element in the singular is not intended to mean "one and only one" unless specifically so stated, but rather "one or more." Unless specifically stated otherwise, the term "some" refers to one or more.

[0030] Accordingly, the scope should be judged in terms of the claims that follows.

[0031] Figure 1 illustrates an audio device 10 that has a MEMS loudspeaker unit array 12 for generating an acoustic output signal. MEMS loudspeaker unit array 12 is comprised of MEMS loudspeaker units 14, each MEMS loudspeaker unit 14 being a micro-electro-mechanical speaker element. The MEMS loudspeaker unit array 12 is controlled by a speaker control unit 16 that generates a multichannel control signal driving the individual MEMS loudspeaker units 14. Speaker control unit 16 is configured to generate the multichannel control signal from an electric audio signal received from a processing unit 18.

[0032] Acoustic sound may be picked up by a microphone 20 that converts the acoustic signal into an electric audio input signal. The electric audio input signal is processed by processing unit 18 that generates an electric audio output signal. The electric audio output signal is fed to speaker control unit 16 that generates the multichannel control signal for driving the MEMS loudspeaker units 14. As illustrated in further detail hereinafter, speaker control unit 16 comprises a MEMS scheduler.

[0033] Figures 2 a), b) and c) illustrate an array 12 of binary MEMS loudspeaker units 14. MEMS loudspeaker units 12 that can move between two states so that one or more MEMS loudspeaker units 14' can move forward into a forward state (high state) while other MEMS loudspeaker units 14" maintain their retracted state (low state). As illustrated hereinafter, MEMS loudspeaker array 10 can replace a conventional loudspeaker with coil and cone.

[0034] Typically, each MEMS loudspeaker unit 12 can be individually controlled by a MEMS scheduler that controls the MEMS loudspeaker units 14; see figure 1. MEMS scheduler receives an electric audio signal from an audio source or other audio processing means 16 and controls MEMS loudspeaker units 14 depending on the audio signal to generate an acoustic output signal that corresponds to the electric audio signal. MEMS loudspeaker units 14 generate elementary waves 22 that interfere and thus generate the desired acoustic output signal.

[0035] Each MEMS loudspeaker unit 14 has a diaphragm that can move between a retracted state (low state) and the forwarded state (high state) according to a control signal from the MEMS scheduler. Compression of the air volume close to each diaphragm creates the elementary sound waves that interfere to thus generating the total sound wave - unlike traditional coil and cone loudspeakers where it is the displacement of the sound by the cone that generates the total sound wave.

[0036] Speaker control unit 16 including MEMS scheduler controls the MEMS loudspeaker units 14 with a high-frequency signal that imparts a high velocity on the MEMS loudspeaker unit's diaphragm. Accordingly, the MEMS loudspeaker unit array creates the sound by operating a multitude of small binary diaphragm units at a high velocity corresponding to a high frequency which creates a powerful pulse from the small diaphragm.

[0037] Figure 3 shows how an increasing number of the MEMS loudspeaker units 14 are moved forward in three steps, each step contributing to an increase of the sound pressure (P)). The first increase came from 1 MEMS unit (figure 2a)), the second increase from 7 MEMS units (figure 2b)), and the third increase from 25 MEMS units. Thus, a total sound pressure is generated that resembles the sound pressure generated by the traditional loudspeaker. From an audibility perspective the difference between the traditional and digital MEMS unit array loudspeaker output is probably above the low pass cut off frequency of human hearing, and thus not audible.

[0038] Another way to describe the digital MEMS unit array loudspeaker's ability to generate sound pressure similar to the bigger traditional loudspeaker comes from the loudspeaker equation,

$$P = \frac{\sqrt{2} \cdot \pi \cdot \rho \cdot S \cdot f^2 \cdot \left(\frac{A}{2}\right)}{r}$$

where

P stands for the RMS pressure produced by the vibrating piston [N/m^2];
A stands for the peak-to-peak vibration amplitude [m];
S stands for the surface area of the vibrating piston [m^2];
☐ stands for the density of the medium (i.e. air) in which the piston is vibrating [Kg/m^3];
r stands for the distance of the measurement point from the face of the piston [m]; and
f stands for the vibration frequency [Hz] or the time-inverse of the effective travel-speed, respectively.

[0039] Figure 4 illustrates that the prior art MEMS units array's ability to generate low frequency sounds is limited by the number of binary elements of the array, because the steps of the sound pressure levels that can be achieved define a minimum increase.

[0040] Figure 5 illustrates a MEMS loudspeaker unit array 20 with MEMS loudspeaker units 22 that can adopt three states, namely a retracted state, an intermediate state and a forward state. While the three activated MEMS loudspeaker units 22' in figure 5a) are all in their forwarded state, MEMS loudspeaker unit 22" in figure 5b) are in their intermediate state while the remaining MEMS loudspeaker units 22 are in their retracted state. Each state is represented by a respective position of the MEMS loudspeaker unit diaphragm. Accordingly, the sound pressure P created by an individual MEMS loudspeaker unit 22 can be varied by varying the travel or amplitude **A** in a state change.

[0041] Alternative, instead of or in addition to providing three spatial states of the MEMS loudspeaker unit's diaphragms, it is possible to provide state changes with different speed, i.e. by providing two different frequencies **f** for driving the MEMS loudspeaker units 22. Accordingly, the sound pressure **P** created by an individual MEMS loudspeaker unit 22 can be varied by varying the travel speed of the diaphragm by applying another frequency **f** in a state change.

[0042] A third way of achieving an intermediate state is to change the effective surface area of the diaphragm of the MEMS loudspeaker unit. This can be combined with the other ways to achieve an intermediate state to thus allow for a plurality of intermediate states. Changing the diaphragm surface - and thus the MEMS loudspeaker unit's impedance - is illustrated in figures 9 and 10 below.

[0043] Adding alternative state changes to the MEMS unit enables the reuse the individual MEMS units faster than prior art MEMS units, and thus generate decrease the number of MEMS units required to generate low frequency output. Size is an important factor for hearing instruments for being able to design stylish instruments and because space can be quite limited in the ear canal. Low frequency sound is especially important for music, and thus this invention is similarly relevant for (in ear) headphones.

[0044] Figure 6 shows the two states of the MEMS unit high state 100 and low state 109. State changes 104 and 106 are used to create sound as described by above. The alternative route between high state 100 and low state 109 through the attenuated high-to-low state transition 102 and attenuated low-to-high state transition 105 enables the MEMS loudspeaker unit 14 to change state without creating as much sound as with state changes 104 and 106.

[0045] In the embodiment shown in figure 7 the MEMS scheduler 208 is connected to the digital output of a synthesis filterbank 206 and the MEMS unit array 12 is connected to the output of the MEMS scheduler 208. Thus, the MEMS scheduler 208 is put into the signal path of the audio device 10. The signal path comprises a front end 200, an analysis filterbank 202 connected to the output of the front end 200, a processing unit 204 connected to the output of analysis filterbank 202 and the synthesis filterbank 206 that is connected to the output of the processing unit 204. The front end 200 is where the device picks up the sound, i.e. from microphones, direct audio, or streaming. The front end produces an electric audio signal 201 that is the fed into the analysis filterbank 202 if the electric audio signal 201 is not already in the time/frequency domain. If the electric audio signal 201 is already in the time/frequency domain, an analysis filterbank is not needed. The analysis filterbank 202 produces a time/frequency-domain audio signal 203 that is then taken to processing unit 204 that carries out some processing steps as defined by the audio device, e.g. noise reduction and amplification to name two in hearing aid processing. Processing could also merely be a frequency dependent gain for a headphone unit. The processed time/frequency-domain audio signal 205 is fed through synthesis filterbank 206 to generate the output audio signal 207 and a signal 211 representing the level in the different frequency bands. The output audio signal 207 together with the signal representing the level in the different frequency bands 211 is fed to the MEMS scheduler 208 which transforms the audio signal 207 into a sequence of state changes for each MEMS unit 12. This multichannel control signal 209 is then fed into the MEMS array unit which operates the MEMS unit according to the schedule and creates sound.

[0046] Figure 8 shows an implementation of the MEMS scheduler. The MEMS scheduler comprises a sequencer 301. Sequencer 301 generates the control signal 209 that controls movement (state transitions) of the MEMS loudspeaker units 14. Sequencer 301 is configured to analyse a current audio signal using a look ahead unit 305 and a spectrum unit 306. The spectrum unit 306 produces a spectrum signal 304 representing the audio signals spectrum. Sequencer compares the spectrum signal 304 to the properties of the MEMS array 12 to determine if the output from the sequencer 301 requires the use of alternative state change modes, if this is the case the audio signal is analysed in the look ahead unit 305 that calculates when the alternative sequences are required.

[0047] A masking model unit 300 also analyses the audio signal and spectrum signal to find the optimal scheduling of the attenuated state changes where the created sound is masked by the sound signal already outputted or just about to be outputted (backward, forward and simultaneous masking). Masking unit 300 generates a scheduling signal 302 that is forwarded to sequencer 301.

[0048] The masking model unit 300 can also be activated to limit the number of state changes in the MEMS loudspeaker units array 12 to save power.

[0049] Moreover the masking model unit 300 can contain the wearers personal profile, which for people with hearing impairment leads to reduced sensitivity to errors introduced by the MEMS scheduler and thus enables further power reductions or increased reuse of MEMS units.

[0050] An embodiment of the invention can utilize two different ways of implementing the attenuated state changes between high and low states, either by electrical or mechanical means.

[0051] Prior art micro-electro-mechanical speaker elements can only shift at one speed. In a preferred embodiment, the MEMS loudspeaker units 14 can also shift at a much lower speed taking more than one clock-cycle - called the refractory period (N cycles). Due to the lower velocity, the resulting "opposite" sound pressure level impact is low.

[0052] Such lower speed can be achieved by controlling a frequency content of a control signal which drives the micro-electro-mechanical speaker elements. In particular, low-pass filtering of the driving control signal with a lower cut-off frequency can lower the speed. Thus, an embodiment can involve two capacitive low pass networks with low and high cut-off frequency and besides from that use a design similar to that known from the prior art.

Table 1

Step	Diaphragm position	Velocity	Acoustical response
1	Low->High	High (106)	Adding to sound pressure
2	High->Low	Low (101, 102, 107)	Limited
3	High->Low	Low (101, 102, 107)	Limited
...	High->Low	Low (101, 102, 107)	Limited
N	Low->High	High (106)	Adding to sound pressure

[0053] Table 1 illustrates an example of operation with two mode MEMS loudspeaker units. The numbers in the Velocity column refers to the state diagram in Figure 6.

[0054] After the slow shift the MEMS loudspeaker unit is ready for a quick shift that adds more to the sound pressure level. Thus, each MEMS loudspeaker unit can be reused to move twice in the same direction in a single cycle if the half cycle duration is longer than the refractory period. This way the MEMS loudspeaker unit array can deliver a louder output at lower frequencies than prior MEMS speakers.

[0055] An attenuated low-to-high or an attenuated high-to-low state transition is a slow state transition with low speed, while an unattenuated low-to-high or an unattenuated high-to-low state transition is a fast state transition with higher speed.

[0056] Figures 9 and 10 illustrate embodiments of a MEMS loudspeaker unit that has a variable acoustic impedance.

[0057] In Figures 9 and 10 the MEMS loudspeaker unit has diaphragm 400 with a two-layer diaphragm structure that can alter its acoustical impedance. Each layer 402 and 404 has holes 406 and 408, respectively, which can be aligned so that the resulting diaphragm has holes, see figure 10.

[0058] Figure 9 illustrates a state where the holes are not aligned. In this state the MEMS loudspeaker unit has the acoustical impedance corresponding to a small diaphragm without holes.

[0059] Figure 10 illustrates a state where the holes 406 and 408 are aligned resulting in a diaphragm 400 with four holes, see figure 10 c. In the state illustrated in figure 10 the MEMS loudspeaker unit has a lower acoustical impedance such that it can move without displacing so much air as in the other state.

[0060] Accordingly, in a preferred embodiment, the acoustical impedance is modified in a two-layer structure that can align holes to achieve low acoustical impedance and or disalign holes to achieve high acoustical impedance.

[0061] The two acoustical modes of the diaphragm illustrated in figures 9 and 10 lead to a new operational pattern for each MEMS loudspeaker unit where it can add to (or subtract from) the sound pressure every forth clock cycle as outlined in Table 2:

Table 2

Step	Diaphragm position	Impedance state	Acoustical response
1	Low-High	High (106)	Adding to sound pressure
2	High	High-Low (101)	Limited
3	High-Low	Low (102)	Limited
4	Low	Low-High (107)	Limited
5	Low-High	High (106)	Adding to sound pressure

[0062] In table 2, the numbers in the Impedance state column refers to the state diagram in Figure 6.

Claims

1. Audio device (10) comprising a speaker control unit (16) and an electro-acoustic transducer unit (12) that comprises a multitude of micro-electro-mechanical speaker elements (14), wherein the speaker control unit (16) is operationally connected to the micro-electro-mechanical speaker elements (14) and configured to drive the micro-electro-mechanical speaker elements (14) so as to reproduce a desired audio signal, each micro-electro-mechanical speaker element (14) being configured to perform a low-to-high state transition and a high-to-low state transition,
   characterized
   in that the speaker control unit (16) is configured to drive the micro-electro-mechanical speaker elements (14) so that they can perform an unattenuated low-to-high state transition leading to a relatively higher sound pressure level and an attenuated low-to-high state transition state transition leading to a relatively lower sound pressure level as well as an unattenuated high-to-low state transition leading to a relatively higher sound pressure level and an attenuated high-to-low state leading to a relatively lower sound pressure level, and
   in that the speaker control unit (16) is further configured to drive the micro-electro-mechanical speaker elements to perform either an unattenuated low-to-high state transition or an attenuated low-to-high state transition state transition, respectively, and an unattenuated high-to-low state transition or an attenuated high-to-low state, respectively, depending on a sound pressure level required to reproduce the desired audio signal.

2. Audio device according to claim 1, wherein at least some micro-electro-mechanical speaker elements (14) are

switchable between a high acoustical impedance state and a low acoustical impedance state so that an unattenuated low-to-high state transition and an unattenuated high-to-low state transition is achieved in the micro-electro-mechanical speaker element's high acoustical impedance state whereas an attenuated low-to-high state transition and an attenuated high-to-low state transition is achieved in the micro-electro-mechanical speaker element's low acoustical impedance state.

3. Audio device according to claim 1 or 2, wherein the speaker control unit comprises a micro-electro-mechanical speaker element scheduler (208) that is configured to transform an output audio signal into a multichannel control signal that represents a sequence of state changes for each micro-electro-mechanical speaker element of the multitude of micro-electro-mechanical speaker elements.

4. Audio device according to claim 3, further comprising

- a front end (200) for receiving a time-domain input audio signal,
- an analyzing (202) filter bank for analyzing the received time-domain input audio signal and generating a time/frequency-domain audio signal,
- a processing unit (204) for processing the time/frequency-domain audio signal,
- a synthesis filter bank (206) for generating the output audio signal and a level signal from the time/frequency-domain audio signal and feeding the output audio signal and a level signal to the micro-electro-mechanical speaker element scheduler (208).

5. Audio device according to claim 3 or 4, wherein the micro-electro-mechanical speaker element scheduler comprises:

- a look ahead unit (305),
- a spectrum unit (306),
- a masking model unit (300), and
- a sequencer (301).

6. Audio device according to at least one of claims 1 to 5, wherein speaker control unit (16) is configured to drive the micro-electro-mechanical speaker elements (14) so that they can travel with two different speeds between the high state and the low state or vice versa, respectively, a high speed resulting in a fast state change and thus in an unattenuated low-to-high state transition or a unattenuated high-to-low state transition, respectively, whereas a lower travel speed results in a slow state change and thus in an attenuated low-to-high state transition or a attenuated high-to-low state transition, respectively.

7. Audio device according to at least one of claims 1 to 6, wherein at least some of the micro-electro-mechanical speaker elements (14) comprise a diaphragm (400) with a surface area that can be varied to impart different acoustic impedances.

8. Audio device according to claim 7, wherein the diaphragm comprises at least two layers (402, 404) with holes (406, 408) wherein the two layers are configured to change their respective rotational position wherein in one rotational position the holes(406, 408) of both layers (402, 404) are aligned, resulting in a diaphragm (400) with a lower effective surface area and thus a lower acoustic impedance, while in another rotation position, the holes (406, 408) of the layers (402, 404) are disaligned resulting in a diaphragm without holes and thus a large effective surface and a higher acoustic impedance.

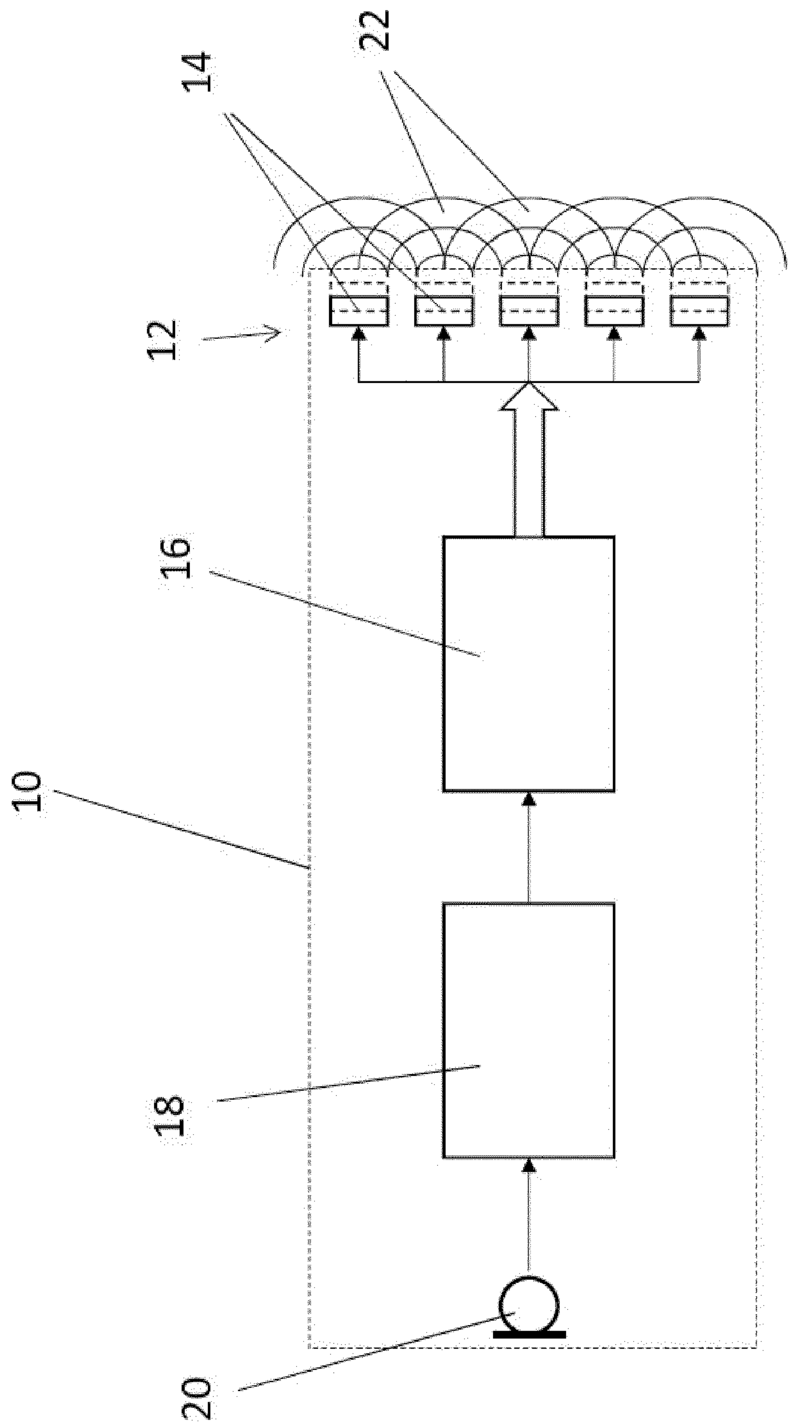

Fig. 1

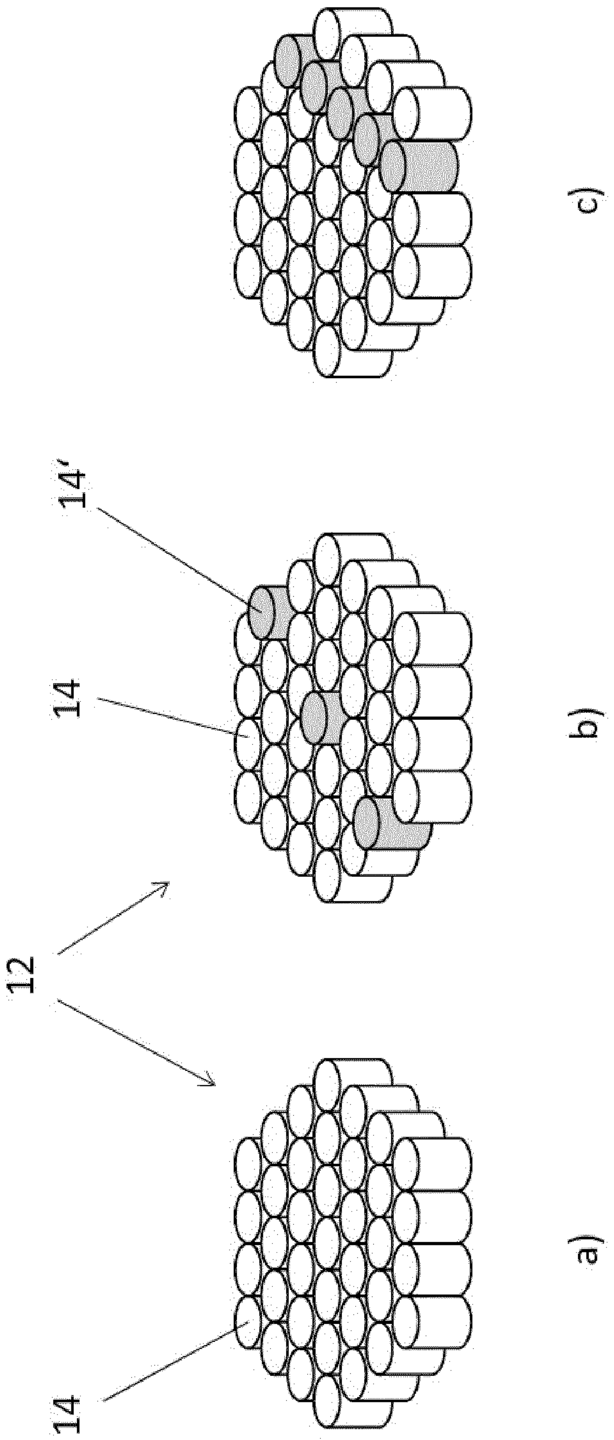

Fig. 2

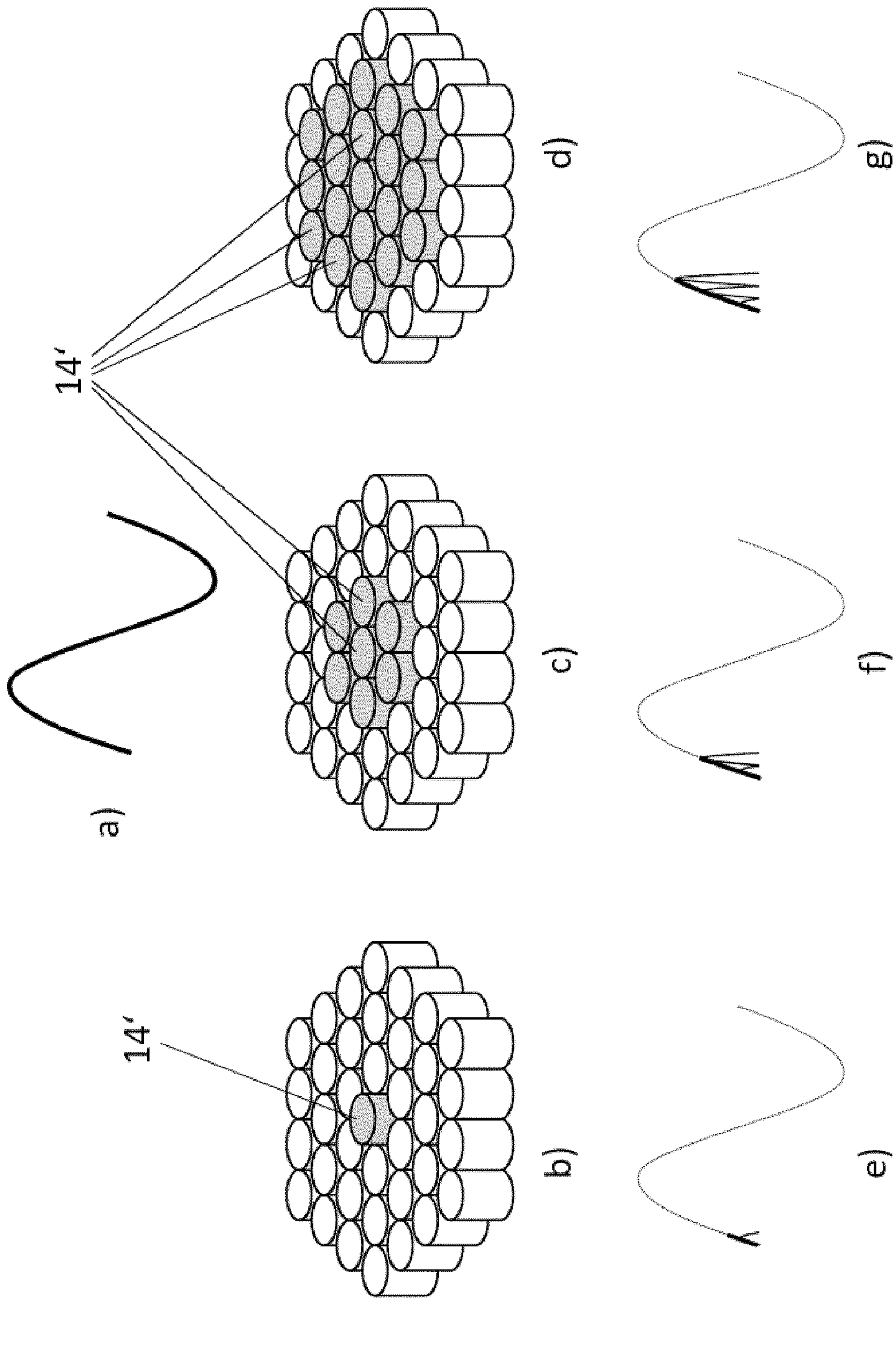

Fig. 3

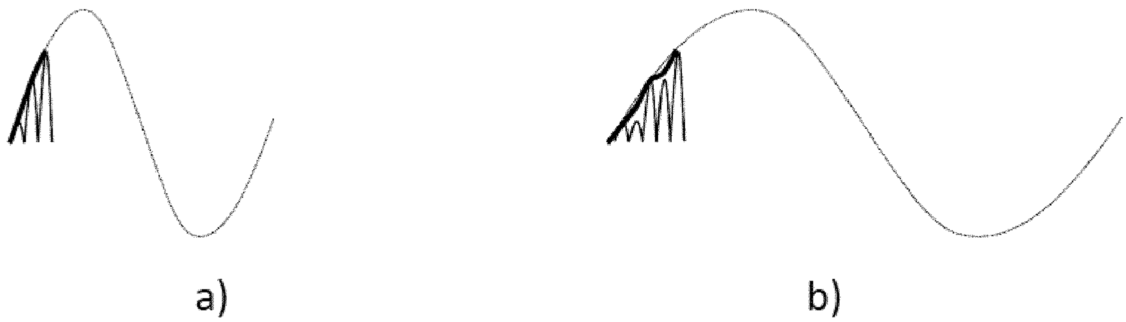

Fig. 4

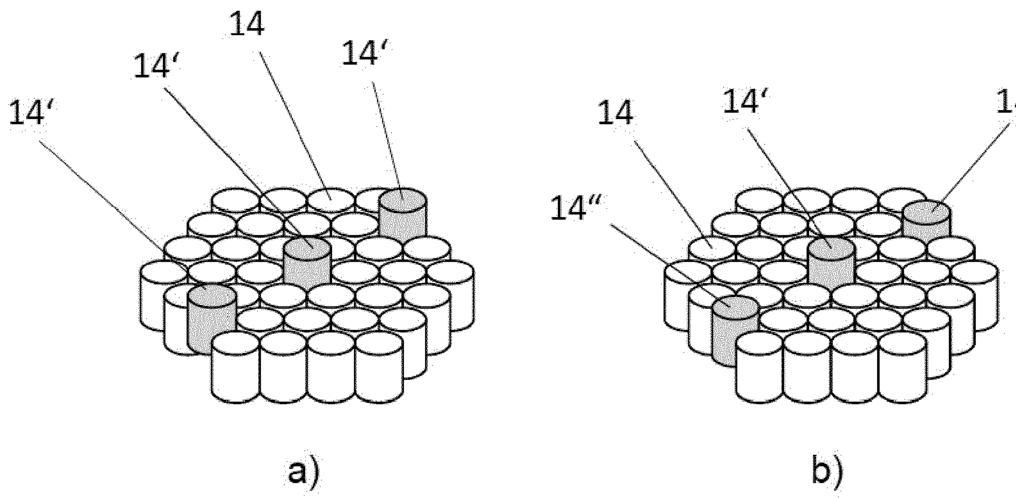

Fig. 5

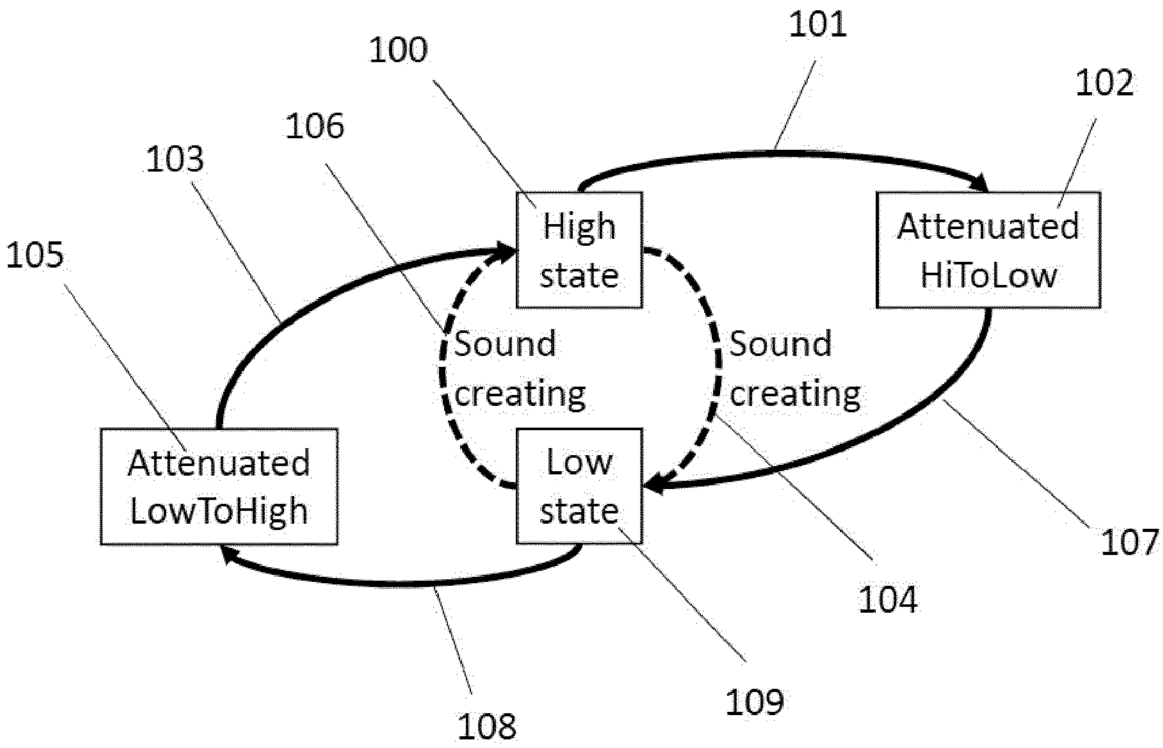
100
101
102
103
106
105
High
state
Attenuated
HiToLow
Sound
creating
Sound
creating
Attenuated
LowToHigh
Low
state
107
104
109
108

Fig. 6

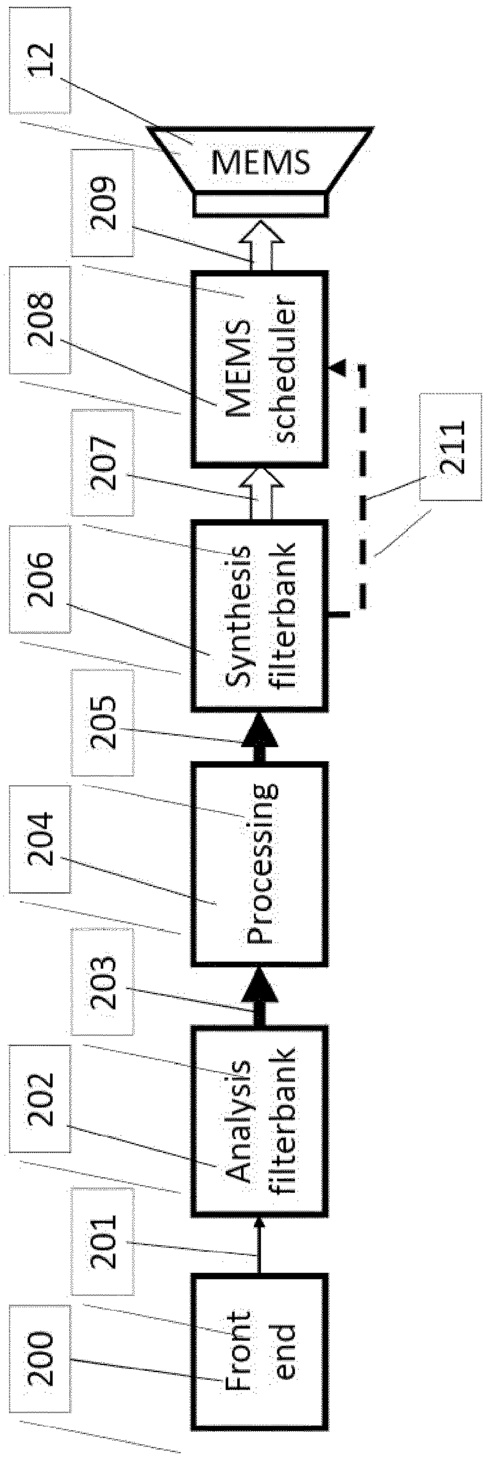
200
Front end
201
202
Analysis filterbank
203
204
Processing
205
206
Synthesis filterbank
207
208
MEMS scheduler
209
211
12
MEMS

Fig. 7

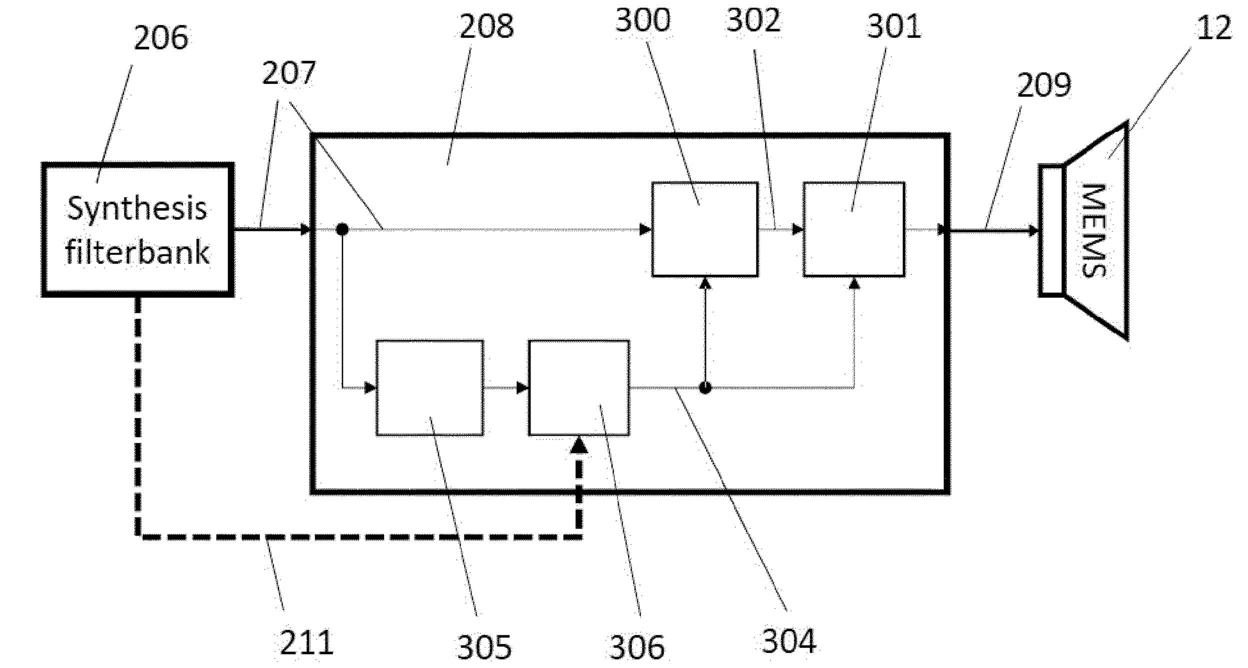
206
207
208
300
302
301
12
209
Synthesis
filterbank
MEMS
211
305
306
304

Fig. 8

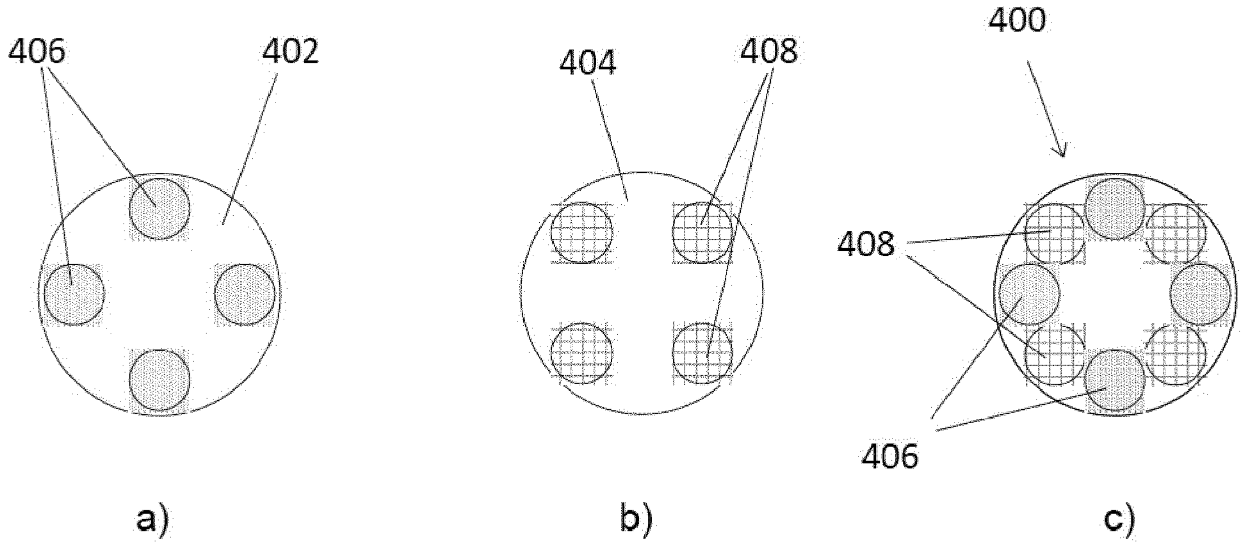
406
402
404
408
400
408
406
a)
b)
c)

Fig. 9

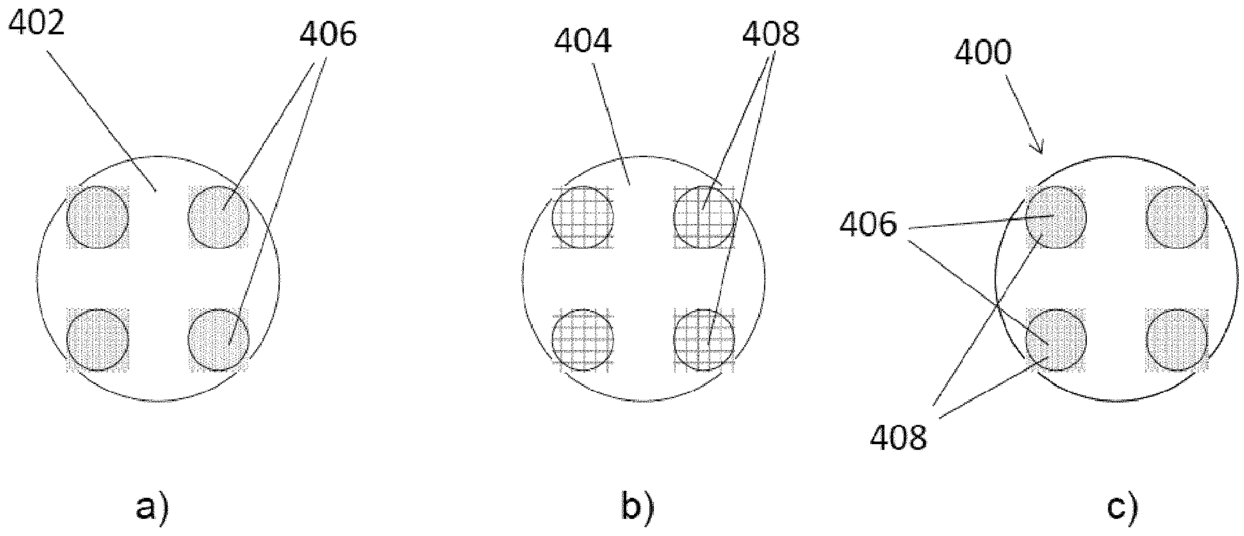

Fig. 10

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EUROPEAN SEARCH REPORT

Application Number
EP 18 16 0932

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H04R

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	16 August 2018	Borowski, Michael

CATEGORY OF CITED DOCUMENTS

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