

APPARATUS FOR CONVERTING AN ELECTRIC SIGNAL INTO AN ACOUSTIC SIGNAL

The invention relates to apparatus for converting an electric signal into an acoustic signal, which apparatus comprises an input terminal for an electric input signal, an electro-acoustic transducer unit, and an amplifier circuit for driving the electro-acoustic transducer unit, which amplifier circuit has an input coupled to the input terminal and an output coupled to the electro-acoustic transducer unit. The transducer unit in known apparatuses of this type generally has a quality factor (see subsequently) which is at least substantially equal to 1. The known transducer unit has a frequency-response characteristic which is comparatively flat in a frequency range between the resonant frequency of the transducer unit and the break-up frequency of the transducer unit, for which reference is made to "Theory and numerical calculation of the vibration and sound radiation of cone and dome loudspeakers with non-rigid diaphragms", preprint No. 1437 (D-1) of the 62nd Convention of the Audio Engineering Society, held from 13 to 16 March, 1977 in Brussels, in particular Figures 5a and 6.

Such known transducer units are driven by amplifier circuits (amplifiers) which have a flat frequency-response characteristic. However, the known apparatus has the drawback that its efficiency, which is defined as the ratio of the acoustic output power of the transducer unit to the electric input power applied to the input terminal, is rather low.

It is an object of the invention to provide an apparatus having a substantially higher efficiency. According to the invention the apparatus is characterized in that the electro-acoustic transducer unit has a quality factor which is smaller than unity, and the amplifier circuit has a voltage gain factor which varies with frequency in a frequency range between a first frequency, which is substantially equal to the resonant frequency of the transducer unit, and a second frequency which lies above the first frequency, this variation with frequency, when said gain factor is expressed in dB, having a form which is

substantially the inverse of that of the variation, expressed in dB, of the output power of the transducer unit with input frequency in said frequency range when the input voltage amplitude to said transducer unit is constant. If the transducer unit comprises a plurality of substantially identical transducers, such as in a loudspeaker column, the said quality factor and the said resonant frequency are to be understood to be those of an individual one of these transducers. If on the other hand the transducer unit comprises a plurality (for example two or three) of non-identical transducers, such as in a two- or three-way system, the said quality factor and the said resonant frequency are to be understood to be those of the transducer having the lowest resonant frequency. The quality factor and resonant frequency of a transducer in the form of a loudspeaker can, of course, be determined by measuring its diaphragm velocity as a function of frequency and determining the position and width of the relevant peak therein.

It has now been recognised that the efficiency of the electro-acoustic transducer unit, which is defined as the ratio between the acoustic output power of the transducer unit and the electric input power applied to the transducer unit, depends on the quality factor of the transducer unit. (For a formula for the quality factor in a particular case reference is made to the following description with reference to Figure 1.) Computations have shown that if the quality factor of the transducer unit (in prior art cases generally equal to approximately 1) is reduced the efficiency of the transducer unit increases over the entire operating frequency range of the transducer unit. This means that a higher acoustic output power is obtained with the same electric input power.

However, the frequency-response characteristic of the transducer unit changes when the quality factor of the transducer unit is reduced. The low-frequency roll-off, which for transducer units having a quality factor substantially equal to 1 starts at the resonant frequency and falls off towards lower frequencies with

a slope of 12 dB/octave, is shifted towards higher frequencies. From a second frequency, which is higher than the resonant frequency of the transducer unit, the frequency-response characteristic of a transducer unit having a Q smaller than unity falls off towards lower frequencies at a rate of approximately 6 dB/octave, changing into a roll-off at a rate of 12 dB/octave from a third frequency which is lower than the resonant frequency. Unless further steps are taken this results in a reduction of the operating-frequency range of the transducer unit because the lower range limit (for transducer units whose $Q = 1$ approximately equal to the resonant frequency of the transducer unit) has shifted towards a higher frequency, namely the said second frequency.

A further reduction of the quality factor leads to an increase in the value of the second frequency and thus to a further reduction of the operating-frequency range of the transducer.

This means that, in isolation, a transducer unit is obtained which has a higher efficiency but a smaller operating-frequency range. In order to obtain an apparatus which reproduces frequencies down to at least the resonant frequency of the transducer unit the amplifier circuit for driving the transducer unit must provide compensation for the roll-off, between the first and the second frequency, in the frequency-response characteristic of the transducer unit. This can be achieved by giving the amplifier circuit a frequency-dependent voltage gain factor, more particularly a voltage gain factor which, in the frequency range between the first and the second frequency, varies with frequency in an inverse manner to the frequency response characteristic of the transducer unit in this range. If this is done the frequency response of the amplifier circuit will increase towards lower frequencies in this range.

If a conventional amplifier is constructed to have the properties set forth in the foregoing in many cases it will be liable to have a low efficiency, which will tend to cancel out the increase in efficiency of the transducer unit. Thus, for example, if a conventional class-A, class-B or a class-AB amplifier having a

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fixed power supply voltage is used, this power supply voltage will have to be sufficient to enable the amplifier to cope with the maximum output amplitude that is to be expected in the amplifier. This maximum amplitude will generally occur in the frequency range around the resonant frequency because the amplifier has a gain factor which is comparatively high in this range. This means that the power supply should be chosen to accord with the signal amplitudes in this frequency range. As a result of this, the amplifier is liable to be no longer driven to the full extent in the frequency range above the second frequency, in which range the gain factor will be substantially lower. This has a negative effect on the amplifier efficiency because class-A, B or AB amplifiers have a maximum efficiency at maximum output level, the efficiency decreasing in the case of smaller output levels (as indicated in the foregoing for signals having frequencies higher than f_2). For example, for class-A amplifiers the efficiency is substantially proportional to the square of the output level. For class-B amplifiers the efficiency is directly proportional to the output level. Accordingly, in apparatus according to the invention the amplifier circuit is preferably constructed to exhibit, at least when its output signal level lies in a higher-level portion of a range of output signal levels which extends from zero to a level which is substantially less than the maximum output signal level which the amplifier circuit is capable of producing, an electrical efficiency which is higher than that of a conventional class B amplifier which has a fixed supply voltage and is such as to be capable of producing the same maximum output signal level as is said amplifier circuit. If such an amplifier circuit is employed the efficiency can remain high, in spite of the circuit being given the required frequency response.

It should be noted that transducer units having a quality factor smaller than unity are known per se. However, the combination of such a transducer unit with an amplifier circuit of the type specified hereinbefore is thought not to be known. It is

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also known to drive electro-acoustic transducer units from an amplifier circuit whose frequency-response in a specific frequency range is the inverse of the frequency-response of the transducer unit in this range, so as to provide compensation for a non-flat portion in the frequency-response characteristic of the transducer unit. This is known, for example, from United States Patent Specification no. 4,118,600, see in particular column 1, lines 20 to 23. However, this specification does not mention a transducer unit having a quality factor smaller than unity, nor an increased efficiency.

Unless the electro-acoustic transducer unit comprises an electro-acoustic transducer incorporated in a bass-reflex cabinet the quality factor of the electro-acoustic transducer unit is preferably between 0.2 and 0.8, and preferably substantially 0.4. If on the other hand the transducer unit does comprise an electro-acoustic transducer incorporated in a bass-reflex cabinet the quality factor of the transducer unit is preferably between 0.1 and 0.6, and preferably substantially 0.3.

The preference for the value 0.4 (or 0.3) is mainly determined by the fact that the efficiency of the electro-acoustic transducer unit is likely then to be substantially constant, (i.e. substantially frequency independent), in the operating-frequency range of the transducer unit. The upper figure of 0.8 (or 0.6) arises from the fact that the increase in efficiency is not particularly significant with higher values. The lower figure of 0.2 (or 0.1) arises from the fact that the frequency dependence of the efficiency increases as the quality factor decreases, which is a disadvantage. Moreover, the difference between the response of the transducer unit for the first frequency and the response for the second frequency (and thus the degree of compensation in the amplifier circuit) increases as the quality factor decreases. For quality factors smaller than 0.2 (or 0.1) the degree of compensation becomes so high that it cannot readily be achieved by the amplifier circuit without a substantial loss of efficiency of the amplifier circuit. For the last-mentioned reason the gain

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factor of said amplifier circuit in a frequency range below said first frequency is preferably either substantially constant or decreases with decreasing frequency on going from approximately said first frequency. (In principle it is alternatively possible for the amplifier circuit to have a rising gain factor on going from the first frequency to lower frequencies, resulting in an apparatus with a wide operating-frequency range, namely an operating-frequency range which extends to below the resonant frequency of the transducer unit).

As already stated, the amplifier circuit preferably comprises an amplifier which, compared with conventional amplifiers, has an improved efficiency at output levels below the maximum. Tests have shown that this may be achieved by employing an amplifier circuit, for example a class-D amplifier, which has an output stage the power supply to which is switched on and off in a periodic manner and in dependence upon the amplifier drive level. Another possibility is to employ an amplifier circuit comprising an amplifier whose power supply voltage depends on the output signal level of the amplifier.

Embodiments of the invention will now be described in detail, by way of example, with reference to the accompanying diagrammatic drawings. In the drawings

Figure 1 shows an embodiment of the invention in highly schematic form,

Figure 2 is a graph showing the efficiencies of a number of electro-acoustic transducer units as a function of frequency, these units having different quality factors,

Figure 3 shows frequency-response curves of a number of transducer units having different quality factors,

Figure 4 is a graph showing, in an idealized manner, the gain factor of the amplifier circuit as a function of the frequency in two particular embodiments of the invention,

Figure 5 shows an embodiment in which the amplifier circuit is in the form of an amplifier whose power supply voltage depends on

its output signal level,

Figure 6 shows another example of such an amplifier circuit,

Figure 7 shows an embodiment in which the amplifier circuit is in the form of a class-D amplifier,

5 Figures 8a and 8b show efficiency curves of various types of amplifier, and

Figure 9 shows another embodiment of the invention.

Figure 1 schematically shows an embodiment of the invention. In Fig. 1 apparatus for converting an electric signal into an acoustic signal comprises an input terminal 1 for an electric input
10 signal, an electro-acoustic transducer unit 2, and an amplifier circuit 3 for driving the electro-acoustic transducer unit 2. The amplifier circuit 3 has an input 4 coupled to the input terminal 1 and an output 5 coupled to the electro-acoustic transducer unit 2.
15 An electro-acoustic transducer unit is to be understood to mean inter alia, a transducer in isolation or a transducer accommodated in an enclosure, such as a closed box or a bass-reflex cabinet, or a transducer mounted on a baffle, or a combination of a plurality of transducers accommodated in an enclosure or mounted on a
20 baffle. The or each transducer may be, for example, a ribbon-type or moving-coil type loudspeaker, a headphone, or a piezo-electric transducer. The transducer unit 2 has a quality factor which is smaller than 1. The quality factor Q of a transducer unit in the form of a moving-coil loudspeaker is given by

$$25 \quad Q = \frac{1}{R_m + \frac{(Bl)^2}{R_e}} \sqrt{m(k_1 + k_b)}$$

in which

R_m = the mechanical resistance of the mass-spring system comprising the diaphragm (the cone) of the transducer unit and its suspension
30 [Ns/m],

R_e = the electrical resistance of the voice coil [Ω],

B = the magnetic induction in the air gap [Wb/m^2],

1 = the length of the turns of the voice coil located in the air gap [m],

m = the mass of the diaphragm, the voice coil and the voice-coil former, and the air load [kg],

k_1 = the spring constant of the suspension of the diaphragm [N/m], and

k_b = spring constant as a result of the air volume behind the diaphragm if the transducer is accommodated in an enclosure. In other cases this term is zero.

One possible way of reducing the quality factor of such a transducer unit is for example to increase the magnetic induction in the air gap, for example by using a larger magnet.

Computations have shown that the efficiency η of the transducer unit 2, which is defined as the ratio of the acoustic output power P of the transducer unit 2 to the electric input power applied to the terminals 5 ($\eta = P/|U||I| \cos \varphi$, where φ is the phase angle between the voltage U and the current I applied to the transducer unit), depends on the magnitude of the quality factor Q, i.e. the efficiency η increases as Q decreases. Figure 2 shows the results of these computations where the electro-acoustic transducer unit does not comprise an electro-acoustic transducer incorporated in a bass-reflex cabinet. In Figure 2 the quantity $\eta \cos \varphi$ is plotted as a function of the frequency f for a plurality of values of Q, namely Q = 1.5; 1.25; 1.0; 0.8; 0.5; 0.4; 0.3 and 0.2. The quantity $\eta \cos \varphi$ is plotted linearly along the vertical axis. It can be seen that for a value of Q around 0.4 the efficiency curve, if a small area just above the resonant frequency f_1 is ignored, is substantially frequency-independent. It can also be seen that for values of Q equal to 0.2 or smaller the efficiency becomes highly frequency-dependent. Furthermore, it is apparent that for Q between 1.5 and 0.8 the increase in efficiency with decreasing Q is not very great. Therefore, the quality factor is preferably selected to be between 0.2 and 0.8 and preferably to be substantially 0.4. On the other hand, if the transducer unit is an electro-acoustic transducer accommodated in a bass-reflex cabinet,

the quality factor of the transducer unit is preferably between 0.1 and 0.6, and preferably substantially 0.3.

The voltage gain factor A of the amplifier circuit 3 is, moreover, frequency-dependent. Thus this gain factor A may vary as
5 a function of the frequency in the manner indicated in Fig. 4 by the (idealised) curve 6. The voltage gain factor is plotted on the vertical scale, which is a logarithmic scale, and it increases towards the lower frequencies in a frequency range between a first frequency f_1 , corresponding to the resonant frequency of the
10 transducer unit 2, and a second frequency f_2 above f_1 . The curve 6' is a possible alternative characteristic relating to a transducer unit with a higher Q . The reason why the voltage gain factor A is arranged to vary with frequency is as follows. Figure 3 shows curves of the acoustic output power P of three transducer
15 units as a function of frequency for a constant voltage on their input terminals, their Q -factors being 1.0, 0.7 and 0.4 respectively. The output power P is plotted logarithmically along the vertical scale. The frequency-response characteristic of the transducer unit whose $Q = 1$ has a comparatively flat portion
20 between the resonant frequency f_1 and the break-up frequency f_b . Below the resonant frequency f_1 the frequency response curve falls off towards lower frequencies at a rate of 12 dB/oct. The break-up region is situated above f_b . The diaphragm (of a cone-loudspeaker) vibration breaks up in this region. The operating-frequency range
25 of a transducer unit having a $Q=1$ is situated substantially between f_1 and f_b . For a transducer unit having a Q smaller than unity the frequency-response characteristic differs in that the comparatively flat portion, and thus the operating-frequency range of the transducer unit, now extends from a frequency f_2 , f_2 being situated
30 above the resonant frequency f_1 and f_2 being shifted towards higher frequencies as Q decreases. For the transducers whose $Q = 0.7$ and 0.4 this frequency is designated f_2 and f_2' respectively. From this frequency the characteristic falls off towards lower frequencies at a rate of approximately 6 dB/oct., changing into a
35 12 dB/oct. roll-off from a third frequency, f_3 and f_3'



respectively, which is lower than the resonant frequency f_1 .

In order to obtain compensation for the reduction of the operating-frequency range the gain characteristic of the amplifier circuit 3, at least in the frequency range between f_1 and f_2 or f_1 and f_2' , is made to vary in an inverse manner to the frequency-response characteristic of the transducer unit 2 in this range. In Figure 4 this variation is represented by the curves 6 and 6' respectively. For frequencies higher than f_2 (or f_2') the amplifier circuit retains its flat frequency characteristic. In the frequency range between f_1 and f_2 (or f_2') the gain factor increases towards lower frequencies with a slope of approximately 6 dB/oct. For frequencies lower than f_1 the characteristic may rise further, for example up to f_3 or f_3' , in order to obtain a wider operating frequency range (i.e. with a lower limit, this being smaller than f_1), may be flat again, or may fall with a certain slope. Suitably, a flat or falling gain characteristic below f_1 is selected. Figure 4 shows a flat characteristic for frequencies lower than approximately f_1 . A reason for not selecting a further rise in the gain characteristic is that the degree of boosting, which is the difference, a_1 and a_2 respectively (see Figure 4), between the level of the gain characteristic for frequencies above f_2 and f_2' respectively, and that for frequencies lower than f_1 should be limited. As this difference in level also depends on the Q-value (a smaller Q means a greater difference in level and consequently a higher degree of boosting) the said reason is also a reason to select the Q-factor so as to be not much smaller than 0.2.

An amplifier circuit having a gain characteristic as, for example, designated by 6 in Figure 4, may in principle be formed by a conventional amplifier, such as a class-A, class-B or a class-AB amplifier, having a fixed power supply voltage whatever the amplitude of its output signal. In such a case the voltage of the power supply will normally be chosen so that the maximum output amplitude that is to be expected will be produced with a minimal distortion. As the amplifier has its maximum gain factor for

frequencies below f_1 the maximum output amplitude will be likely to occur in this frequency range. For signals of frequencies above f_2 (or f_2') the amplifier will not be likely to be driven to the full extent because of its substantially lower gain factor in this frequency range. As the efficiency of a conventional amplifier is a maximum when the amplifier is driven to the full extent and decreases in the case of a smaller output level, it is likely that the required gain versus frequency characteristic will result in a reduction of the efficiency of the amplifier, possibly to such an extent that the increase in efficiency obtained by the choice of a transducer unit having a lower Q is cancelled almost completely. Therefore preferably an amplifier is employed whose efficiency depends to a lesser extent on its output level. One possibility is to employ an amplifier having a supply voltage which depends on the output level of the amplifier. Figures 5 and 6 show two examples of such an amplifier. Another possibility is to employ a switched amplifier, for example a class-D amplifier. Figure 7 shows an example of such an amplifier. Figure 5 shows an embodiment of the invention which employs an amplifier whose power supply voltage tracks the output level of the amplifier. The amplifier circuit 3 comprises an operational amplifier 10 having an impedance Z_1 between its output and its inverting input and an impedance Z_2 between its inverting input and a point 11 of constant potential, in the present case earth. The gain factor from input 4 to output 5 of the amplifier circuit 3 is equal to $\frac{Z_1 + Z_2}{Z_2}$, assuming that the gain factor of the operational amplifier 10 is very high. The impedances Z_1 and Z_2 are such that the gain factor $\frac{Z_1 + Z_2}{Z_2}$ varies with frequency in a manner corresponding to curve 6 or 6' in Figure 4. The output of amplifier 10 is coupled to a circuit 12 which generates first and second power-supply voltages 13 and 14 respectively, these being fed to the positive and negative

power-supply terminals respectively of the amplifier 10 and varying with the output signal level of the amplifier 10. The operation of the circuit 12 is such that the power-supply voltages 13 and 14 track the output signal level of the amplifier 10.

Figure 6 shows another example of an amplifier circuit 3 for driving the transducer unit 2. The amplifier again comprises an operational amplifier 10. In order to obtain the gain characteristic represented by curve 6 or 6' in Figure 4 a filter device 20 is arranged between the input 4 of the amplifier circuit 3 and the input of amplifier 10. The output 21 of the filter device 20 is also connected to the input of a threshold device 22. The output signal of the threshold device 22 controls two interlocked switches 23 and 24. The positive and negative power-supply terminals of the amplifier 10 are connected to a terminal of the switch 23 and a terminal of the switch 24 respectively. In the position of the switches 23 and 24 shown the amplifier receives fixed power-supply voltages $+S_1$ and $-S_1$, and in the other position of the switches the power supply voltages are $+S_2$ and $-S_2$. The value of the fixed voltage S_1 is selected to be just sufficient to enable an input signal of a frequency below f_1 on input 4 of the amplifier circuit 3 to be amplified without distortion when it has the maximum attainable amplitude. The value of the fixed voltage S_2 is selected to be just sufficient to enable an input signal of a frequency above f_2 on input 4 of the amplifier circuit 3 to be amplified without distortion, even when it has the maximum attainable amplitude. In view of the frequency response of filter 20 this means that, assuming these two maximum attainable amplitudes are the same, S_1 is greater than S_2 , the ratio between them corresponding to the ratio between the levels in the frequency response of the filter 20 below f_1 and above f_2 respectively, which response corresponds to the frequency-response curve 6 or 6' in Figure 4. The threshold value of the threshold device 22 is chosen to be equal to the maximum attainable level of the output signal on the output 21 of the filter for frequencies above f_2 . If the actual level on output 21 is higher than said threshold value

the output signal of the threshold device 22 is such that the switches 23 and 24 are in the position shown. The power-supply voltage applied to the amplifier 10 is then high ($S_1, -S_1$). This happens only for signals of frequencies below f_1 and of an amplitude above the threshold value of the threshold device. If the actual level on output 21 is lower than said threshold value the output signal of the threshold device is such that the switches 23 and 24 are in the other position. In the present case the supply voltage is then low ($S_2, -S_2$). This happens for signals having an amplitude below the threshold value of the threshold device, regardless of their frequency. Thus, a varying power supply voltage is obtained. In this case this is a varying power supply voltage with two discrete levels. Obviously, it is possible to construct amplifier circuits whose power supply voltage can vary between three or more discrete levels depending on the level of the signal to be amplified.

Figure 7 shows an embodiment of the invention in which the amplifier circuit 3 employs a class-D amplifier. The input signal is supplied to the non-inverting input of a differential amplifier 30 via the input 4. The output of this amplifier is connected to one input of a comparator 31. The other input of the comparator 31 is connected to a ramp generator 32 whose output signal is preferably a triangular signal of a high frequency, for example 40 kHz. This defines the maximum frequency which is reproduceable by the amplifier circuit 3, which will be approximately 2 to 4 kHz. This is adequate for an electro-acoustic transducer unit which is intended for the reproduction of bass tones only (a woofer). If high frequencies are to be reproduced by the amplifier circuit the output frequency of the ramp generator must be increased correspondingly. The comparator 31 compares the output signal of the differential amplifier 30 with the output signal of the ramp generator 32 and supplies a (binary) output signal which is high (logic "one") if the amplitude of the ramp signal is higher than the output amplitude of the differential amplifier 30 and which is low (logic "zero") if the amplitude of the ramp signal is smaller. The output signal of the comparator 31 is a signal which

is pulse-width modulated. The section 33 of the circuit serves to delay the falling edges in the output signal of the comparator 31 by a specific time interval. The section 33' of the circuit serves to delay the rising edges in the output signal of the comparator 3 by a specific time interval. The circuit 33 is coupled to the gate of a P-channel field-effect transistor 36 via a buffer 34 and a circuit section 35. Further, the circuit 33' is coupled to the gate of an N-channel field-effect transistor 39 via a buffer 37 and a circuit section 38. The drains of the two transistors 36 and 39 are connected to the output 5 of the amplifier circuit via a low-pass filter 40 and a decoupling capacitor 41. The sources of the transistors 36 and 40 are coupled to the positive supply voltage terminal (+) and to earth (-) respectively. The output signal of the comparator 31 drives the two transistors 36 and 39 in such a way that transistor 39 is turned off (cut off) and transistor 36 is turned on (becomes conductive) when a falling edge occurs in said output signal, so that a signal current then flows from the positive power supply terminal (+) to the output 5 of the amplifier circuit. When a rising edge occurs in the output signal of the comparator 31 transistor 39 is switched on and transistor 36 is switched off, so that a signal current then flows from the output 5 to the negative power-supply terminal (-) via transistor 39. As a result of the low-pass characteristic of the filter 40, whose cut-off frequency corresponds to the highest frequency to be reproduced by the amplifier circuit, i.e. to 2 to 4 kHz, a continuously varying signal is produced on the output 5, which signal is an amplified replica of the input signal applied to terminals 4.

It is evident from the foregoing that the two transistors 36 and 39 conduct alternately. Moreover, care must be taken that they cannot conduct simultaneously because this would result in a large current from the positive power supply terminal (+) to the negative power-supply terminal (-) via transistors 36 and 39, which current would destroy these transistors. In order to prevent this from happening as a result of the turn-on and turn-off delay of the

transistors, the circuits 33 and 33' are provided, which circuits delay the falling edges and thus the switch-on moments of transistor 36 relative to the switch-off moments of transistor 39, and the rising edges and hence the switch-on moments of transistor 39 relative to the switch-off moments of transistor 36 respectively. The circuits 35 and 38 provide protection against the transistors 36 and 39 breaking down as a result of transients occurring in the amplifier circuit, i.e. when the power-supply voltage is suddenly switched on (or raised), or as a result of overdriving. The buffers 34 and 37 serve to amplify the signals in such a way that transistors 36 and 39 are driven with sufficient power. The RC-network 42 serves to compensate for the influence which various stray capacitances in the transistors 36 and 39 and stray inductances (for example as a result of the wiring) would otherwise have on the output signal of the amplifier circuit. A series arrangement of two impedances Z_1 and Z_2 is connected between the output of the amplifier circuit and earth, the junction point between the two impedances being coupled to the inverting input of the differential amplifier 30. The impedances Z_1 and Z_2 provide frequency-dependent negative feedback. Thus, the frequency-dependence of the amplifier circuit, as shown in Figure 4, is achieved in the same way as in the amplifier circuit shown in Figure 5.

Curve 53 in Figure 8a shows the efficiency of the amplifier circuit of Fig. 7 as a function of the relative output level. Figure 8a is a graph in which the relative output level u (the ratio between the actual output level and the maximum output level) is plotted along the horizontal axis and the electrical efficiency η_{el} along the vertical axis. The curves 51 and 52 are included for comparison, and relate to a class-A and a class-B amplifier respectively. It can be seen that the efficiency of a class-A amplifier varies substantially as the square of the output level. At maximum output level the efficiency is approximately 50%. The efficiency of a class-B amplifier is directly proportional to the output level. At maximum output level the efficiency is

approximately 78%. The substantial increase in efficiency for all output levels obtained by using the class-D amplifier shown in Figure 7 rather than the class-A and B amplifiers is clear from curve 53.

Figure 8b is a graph showing the efficiencies of the amplifier circuits described with reference to Figures 5 and 6 as a function of relative output level. The solid line 55 relates to the amplifier circuit shown in Figure 6 when amplifier 10 is a class-B amplifier. The value x corresponds to the ratio S_2/S_1 . For small output levels the power supply is switched to the voltage S_2 , i.e. for relative output levels between 0 and x the well-known curve for the class-B amplifier is obtained. For larger output levels the power supply is set to the voltage S_1 . Relative output levels between x and 1 again result in the well-known curve for the class-B amplifier. The change from the power-supply voltage S_2 to the power-supply voltage S_1 in the case of a relative output level increasing through x results in a drop in the efficiency curve. It is clear that the amplifier circuit of Fig. 6 exhibits, when amplifier 10 is a class B amplifier and its output level lies in the range for which $u < x$, an electrical efficiency which is higher than that of a conventional class B amplifier which has a fixed supply voltage and is such as to be capable of producing the same maximum output level as is the amplifier circuit of Fig. 6. The curve 57 in Fig. 8b relates to the amplifier circuit of Fig. 6 when amplifier 10 is a class A amplifier. It is clear that, in this case, the amplifier circuit exhibits, when its relative output level lies in the range 59, i.e. within a higher level portion 59 of the range for which $0 \leq u \leq x$, an electrical efficiency which is higher than that of a conventional class B amplifier which has a fixed supply voltage and is such as to be capable of producing the same maximum output level as is the amplifier circuit of Fig. 6. Although in this case the efficiency, when $u > x$, is lower than that of the conventional class B amplifier there can still be an improvement in overall efficiency compared with apparatuses comprising a conventional class B amplifier and a transducer unit

having a quality factor of unity. A further improvement is obtainable with the arrangement of Fig. 6 if the supply voltage of amplifier 10 is arranged to be variable between three or more values. The curve 56 in Fig. 8b relates to an amplifier circuit whose power supply continuously tracks the output level of the amplifier circuit, as described with reference to Figure 5, in such manner that it tracks the peaks of the amplifier circuit output signal. It is assumed that a normal class-B amplifier is used for the amplifier 10. If on the other hand the power supply is arranged to track the actual waveform of the amplifier circuit output signal the efficiency can be improved still further, an efficiency of almost 100% being then possible over practically the whole output level range (see line 58) whatever kind of amplifier (Class A, B or AB) is actually used for the amplifier 10. Figure 8b clearly shows that a higher efficiency is obtained in both cases over practically the complete output level range, compared with the standard class-B amplifier having a fixed power supply, see the lines indicated by reference numerals 56 and 58.

It was stated in the description of the class-D amplifier of Figure 7 that the maximum frequency reproduceable by the amplifier circuit is determined by the frequency of the ramp generator 32 and that if higher frequencies are to be reproduced the frequency of the ramp generator must be increased. However, the ramp-signal frequency should not be increased too far because if it were the influence of various stray capacitances would increase and a higher distortion in the output signal of the amplifier circuit would result.

An example of an amplifier circuit which is capable of reproducing a larger frequency range is shown in Figure 9. The amplifier circuit comprises two amplifiers 61 and 62 respectively which both receive the input signal. The transducer unit 2 is arranged between the outputs of the two amplifiers. Amplifier 62 inverts the signal applied to its input whereas amplifier 61 does not. Amplifier 61 has a frequency response which is flat over the entire frequency range to be reproduced (i.e. from around 20 Hz to

approximately f_b , see Figures 3 and 4). Amplifier 62 has a low-pass characteristic which rolls off at a rate of approximately 6 dB/octave from the frequency f_1 . Since the operating range of the amplifier 62 is therefore limited to low frequencies a class-D amplifier as described with reference to Figure 7 may be used for this amplifier. The negative-feedback impedances Z_1 and Z_2 should then be selected to obtain a low-pass characteristic which is such that only frequencies lower than f_2 (or f_2') are reproduced thereby. An amplifier whose power supply voltage tracks its output level may then be used for the amplifier 61. The combination of the two amplifiers yields the frequency response shown in Figure 4. Capacitor 63 is necessary to drain signals having frequencies above f_2 (or f_2') to earth, so as to preclude the draining of these high-frequency signals via amplifier 62, which would contribute to a high dissipation in the amplifier 62. In some cases the output circuit of the amplifier 62 will already include a capacitor which is connected to earth. In such a case no additional capacitor 63 is required.

It should be noted that the invention is not limited to the apparatuses described in the foregoing. For example, it is alternatively possible to employ transducer units which employ ribbon-type transducers.



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CLAIMS:

1. Apparatus for converting an electric signal into an acoustic signal, which apparatus comprises an input terminal for an electric input signal, an electro-acoustic transducer unit, and an amplifier circuit for driving the electro-acoustic transducer unit, which amplifier circuit has an input coupled to the input terminal and an output coupled to the electro-acoustic transducer unit, characterized in that the electro-acoustic transducer unit has a quality factor which is smaller than unity, and the amplifier circuit has a voltage gain factor which varies with frequency in a frequency range between a first frequency, which is substantially equal to the resonant frequency of the transducer unit, and a second frequency which lies above the first frequency, this variation with frequency, when said gain factor is expressed in dB, having a form which is substantially the inverse of that of the variation, expressed in dB, of the output power of the transducer unit with input frequency in said frequency range when the input voltage amplitude to said transducer unit is constant.

2. Apparatus as claimed in Claim 1, characterized in that the amplifier circuit is constructed to exhibit, at least when its output signal level lies in a higher-level portion of a range of output signal levels which extends from zero to a level which is substantially less than the maximum output signal level which the amplifier circuit is capable of producing, an electrical efficiency which is higher than that of a conventional class B amplifier which has a fixed supply voltage and is such as to be capable of producing the same maximum output signal level as is said amplifier circuit.

3. Apparatus as claimed in Claim 1 or 2, characterized in that the quality factor of the electro-acoustic transducer unit is between 0.2 and 0.8.

4. Apparatus as claimed in Claim 3, characterized in that the quality factor is substantially 0.4.

5. Apparatus as claimed in Claim 1 or 2, the electro-acoustic transducer unit being an electro-acoustic transducer accommodated



in a bass-reflex cabinet, characterized in that the quality factor of the electro-acoustic transducer unit is between 0.1 and 0.6.

6. Apparatus as claimed in Claim 5, characterized in that the quality factor is substantially 0.3.

5 7. Apparatus as claimed in any preceding Claim, characterized in that the voltage gain factor of said amplifier circuit in a frequency range below said first frequency is substantially constant or decreases with decreasing frequency on going from approximately said first frequency.

10 8. Apparatus as claimed in Claim 2, or in any of Claims 3 to 7 when appended to Claim 2, characterized in that the amplifier circuit has an output stage the power supply to which is switched on and off in a periodic manner and in dependence upon the amplifier drive level.

15 9. Apparatus as claimed in Claim 8, characterized in that the amplifier is a class-D amplifier.

20 10. Apparatus as claimed in Claim 2, or in any of Claims 3 to 7 when appended to Claim 2, characterized in that said amplifier circuit comprises an amplifier whose power-supply voltage depends on the output signal level of the amplifier.

11. Apparatus for converting an electric signal into an acoustic signal, substantially as described herein with reference to the drawings.

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