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TRANSDUCER CIRCUIT AND METHOD OF OPERATION

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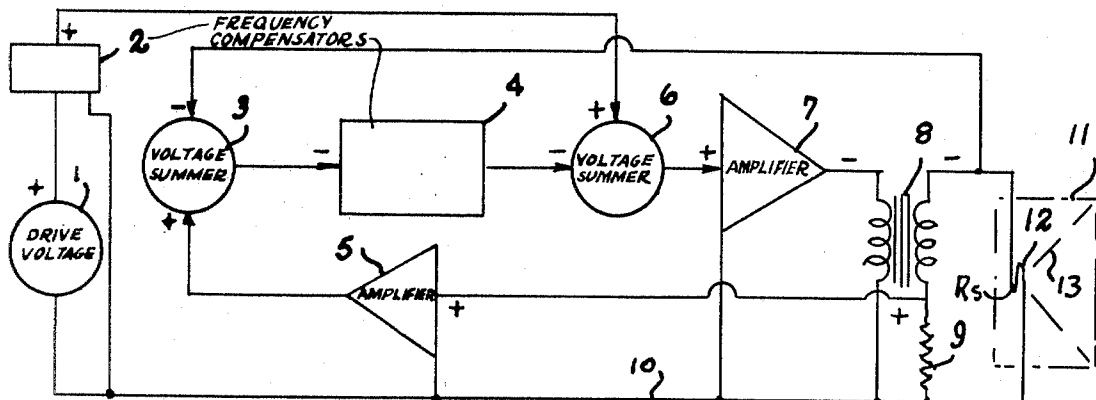


FIG. 1

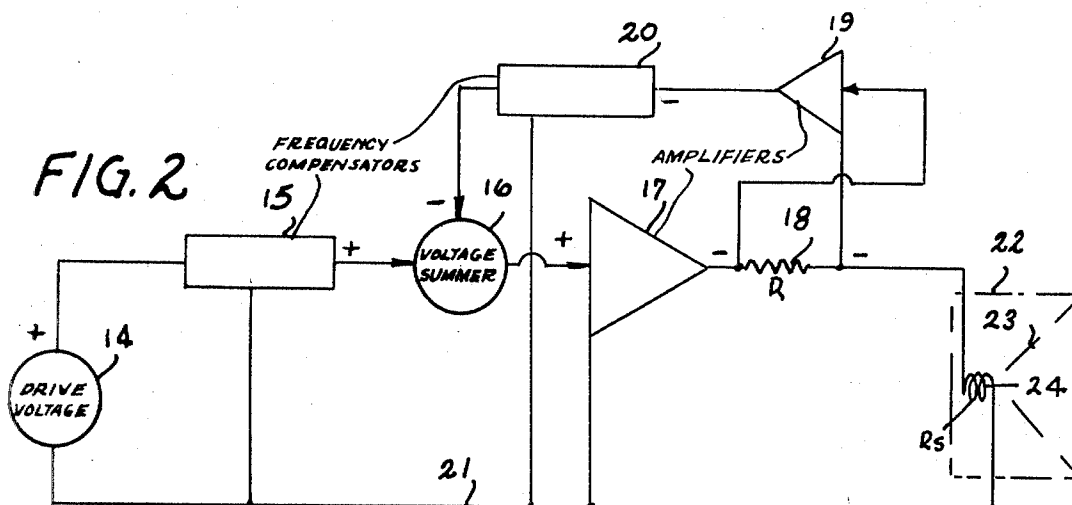


FIG. 2

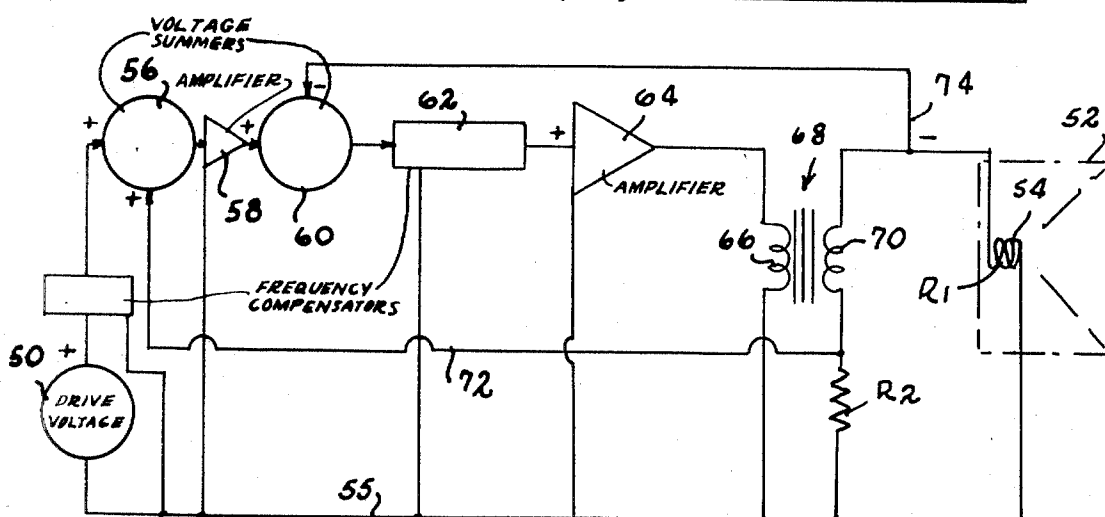


FIG. 3

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TRANSDUCER CIRCUIT AND METHOD OF OPERATION

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7 Claims

ABSTRACT OF THE DISCLOSURE

The invention relates to a loud speaker circuit in which the resistance drop across the speaker coil is measured and is fed back into the driving voltage for the speaker coil after having been inverted so as to be 180° out of phase with the resistance drop across the speaker coil.

The present invention relates to sound producing systems and in particular to improvements therein. More particularly still, the present invention pertains to the reduction of distortion in sound producing systems, especially in sound systems containing an amplifier and a speaker of the moving coil type. Some systems are known which employ a feedback proportional to the movement of the speaker coil. These systems have been called "Motion feedback systems," and others have been called "Amplifiers with negative output impedance equal to the blocked impedance of the speaker."

This application is a continuation of application Ser. No. 500,388, filed Oct. 21, 1965, now abandoned.

In this application, the drive amplifier and transducer (speaker) will be considered the sound producing system. The transducer is defined as a device that is powered by a current flowing through a wire that is disposed in a magnetic field. The wire of the transducer (voice coil) is attached to a diaphragm (cone) that is mounted in a box called an enclosure. The drive amplifier is defined as the electronic circuitry that produce voltage gain, power and other signal preparation required to drive the speaker.

In a conventional sound producing system, the drive amplifier is designed to deliver a voltage that is a constant times the input voltage over some useable frequency range. This constant voltage generator, as it may be called, is connected directly to the speaker. At low frequencies, say, below 1000 cycles per second (c.p.s.) for speakers with good efficiency, the speaker is essentially a resistive load. Therefore, at low frequencies the current in the voice coil is essentially constant with frequency. Movement of the cone is then controlled mainly by this current, in combination with the mass and spring combination of the cone, and acoustical factors such as box resonance and standing waves within the box. The combination of these factors cause the level of the sound that is produced to change as frequency is changed. In addition, the spring constant of the centering device of the cone causes some intermodulation distortion.

Most attempts at improving the performance of this system have been aimed at controlling the natural mechanical response of the cone. These attempts have included very large boxes, boxes with tuned ports, exponential horns, acoustic suspension of the cone, large amounts of acoustical damping, large cone mass, and improvement of the quality of the drive amplifier. The result of these techniques has been either large physical dimensions or low efficiency. These techniques have thus, furthermore, been only moderately successful in producing a high quality sound producing system.

Another approach to the problem of improving the performance of the amplifier-speaker combination is the use of inverse feedback that is proportional to the move-

ment of the cone. With large amounts of feedback and proper compensation for the radiation characteristics of the cone, a sound producing system can be made that has low harmonic distortion and having a sound output very nearly equal over a wide range of frequencies, in small enclosures and without special acoustical absorption, tuned ports, or cones with large mass and acoustical suspension. The effects of standing waves, box resonances and the cone resonance can be substantially reduced. In short, a system with improved performance can be made at less cost.

It is the particular purpose of this invention to make possible the use of large amounts of inverse feedback, proportional to the movement of the cone, while maintaining good amplifier-speaker system stability and while using conventional amplifier components. It is further the purpose of the invention to accomplish this feedback, using a conventional speaker, without adding any special devices to the speaker.

In order to accomplish movement feedback, a voltage proportional solely to the movement of the cone must be produced. One method of accomplishing this is to mount a second coil and magnet in front of the speaker. The second coil is attached to the cone. Movement of the second coil in a second magnetic field generates the desired voltage. This method, however, has several drawbacks. It adds considerable cost to the speaker, lowers the speaker's efficiency because of the increased cone mass, and the mechanical connection between the drive coil and second coil contributes high frequency phase shift that may limit the amount of the feedback to a low value.

A voltage corresponding to that generated by the method described in the preceding paragraph is generated within a conventional speaker in the form of the back induced voltage that results from the movement of the coil in its magnetic field. This voltage is a part of the total voltage across the speaker and accounts for some of the electrical impedance of the speaker and is proportional to the velocity of the cone. A method of extracting this back induced voltage, using a bridge that is balanced to the DC resistance of the speaker, is disclosed in U.S. Pats. 2,887,532 to Werner and 2,167,011 to Tellegen.

This method of generating a feedback voltage also has certain drawbacks. In order to maintain reasonable power efficiency, the resistor opposite the speaker resistance in the bridge must be much smaller than the resistance of the speaker. As a result, the speaker back EMF is divided by the ratio of speaker resistance to the bridge resistor and again by a factor of 2. Since the back EMF is a very small portion of the total speaker voltage at low frequencies, very high amplifier gain is required to convert the detected back induced voltage to a usable signal. The coupling phase shifts occurring in the required additional amplifiers may prevent the use of large amounts of feedback without additional power supplies and direct coupled amplifiers, and adding considerable cost to the amplifier.

With the foregoing in mind, the primary object of the present invention is a method of and a circuit for extracting the back EMF in a speaker or transducer coil and utilizing the extracted back EMF for improving the operation of the speaker or transducer.

The exact nature of the present invention will be more clearly understood upon reference to the following detailed specification taken in connection with the accompanying drawings in which:

FIG. 1 is a somewhat schematic block diagram illustrating one circuit according to the present invention;

FIG. 2 is a view similar to FIG. 1 but shows another circuit; and

FIG. 3 shows still another circuit arrangement according to the present invention.

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FIGS. 1 and 2, are block diagrams of the method of extracting and applying the back induced voltage of a transducer. Polarity of signals, relative to return are indicated by plus and minus signs. Plus signals are generally in phase with the drive voltage, while negative signals are generally out of phase with the drive voltage.

In FIG. 1, a drive voltage source, 1, is connected to the system return wire 10, and to the input of a frequency compensation network 2, which has a connection to return line 10 and the output of which is connected to voltage summer 6, where it is added to the voltage from a frequency compensation network 4. The input of network 4 is connected to the output of voltage summer 3. Two inputs of voltage summer 3, are connected to the voltage across the transducer coil 12, and another to the output of amplifier 5.

The input of amplifier 5 is connected to a resistor that has one end connected to the return wire 10 of the system. The input of 5 is also connected to the secondary winding of transformer 8, the other end of the winding being connected to one side of the transducer coil. The other side of the transducer coil is connected to the return wire 10. Amplifier 5 has a connection to return wire 10. The output of voltage summer 6 is connected to the input of amplifier 7, which also has a connection to the return wire 10. Its output is connected to the primary winding of transformer 8, the other end of which is connected to the return wire 10.

11 represents the enclosure of the speaker, and 13 represents the movable cone of the speaker that is connected to the coil 12, which is disposed in a magnetic field.

In FIG. 2, a drive voltage source 14 is connected between return wire 21 and a frequency compensation network 15, that has a connection to return wire 21. The output of 15 is connected to one of the inputs of voltage summer 16. The other input of 16 is connected to the output of a frequency compensation network 20, that has a connection to return wire 21. The output of voltage summer 16 is connected to the input of amplifier 17, which also has a connection to return wire 21. The output of 17 is connected to a resistor 18, the other end of which is connected to one end of the transducer coil. The other end of the transducer coil is connected to return wire 21. Amplifier 19 has a connection to the junction of resistor 18 and coil 24, while its input is connected to the junction of resistor 18 and amplifier 17. Its output is connected to the input of frequency compensation network 20.

22 represents the enclosure of the speaker and 23 represents the movable cone that is attached to voice coil 24, which is disposed in a magnetic field.

At any one frequency the total voltage across the speaker voice coil 12 or 24 can be considered to be the vector sum of the $I \times R$ drop, or the DC resistance of the speaker, and the back induced voltage resulting from movement of the voice coil wire in the magnetic field. For purposes of this discussion the inductance portions of the voice coil not in the magnetic field has been neglected since it is, in fact, negligible and does not represent the main effect. It will be referred to later.

The back induced voltage can be extracted from the total speaker voltage by adding to the total speaker voltage, an auxiliary voltage equal to the $I \times R$ drop and out of phase with the total voltage. Since the added voltage cancels the $I \times R$ drop in the speaker, the remaining voltage is only the back induced voltage. A voltage equal to the $I \times R$ drop is produced by amplifying the voltage across a small resistor placed in series with the speaker. Phase inversion is achieved within the amplifier or by placement of the resistor in the circuit.

FIG. 1 shows a block diagram of a system using feedback proportional to the speaker back induced voltage. In FIG. 1, resistor 9 is some fraction of the resistance of the speaker coil 12. Resistor 9 is placed so that its voltage is out of phase with the speaker voltage. Amplifier 5

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has controlled gain $A = R1/R$, where $R1$ is the resistance of the speaker and R is the external resistance 9. The output of amplifier 5 is thus a voltage equal to the $I \times R$ drop in coil 12, and is out of phase with the speaker voltage.

The output of voltage summer 3 in FIG. 1 is only the back induced voltage, since the $I \times R$ drop portion of the speaker voltage has been cancelled. This arrangement requires a transformer 8 disposed between output amplifier 7 and speaker coil 12, or a transformer as a part of amplifier 7.

FIG. 2 shows a block diagram of a system that does not require a transformer output. In this arrangement the cancelling $I \times R$ voltage is added directly to the speaker voltage by superimposing the voltage of amplifier 19 on the voltage supply to the speaker. The amplifier 19 also furnishes the required phase inversion. The output of amplifier 19 is only the back induced voltage.

The voice coil usually has a small amount of inductance resulting from wire not in the magnetic field. If desired, the effect of this inductance can be cancelled by adding inductance to the resistor 9 (FIG. 1) or 18 (FIG. 2) in proportion to the ratio of R (9 or 18) divided by the speaker resistance times the inductance of the voice coil. If R (9 or 18) is one-tenth of the voice coil resistance, the inductance added to R would be one-tenth of the voice coil inductance.

The chief advantage of the circuits described above is that R may be made small in comparison to $R1$, thereby giving little power loss, while deriving the back induced voltage without proportionate voltage loss. The circuit of FIG. 2 has the additional advantage of not requiring a transformer output. Other advantages of these circuits will be discussed under stability considerations.

To make a practical system work, careful consideration must be given to phase shifts in various stages of the amplifier-speaker system. Practical circuits have phase errors at both high and low frequencies that cause the system to oscillate when large amounts of feedback are applied, unless proper phase-gain relationships are maintained. In order to avoid oscillation, the gain of the amplifier must be reduced before consecutive phase shifts result in positive feedback.

The stability of the system will be a function of the gain versus phase characteristic of the open loop gain of the system. The open loop gain must be below 1 at frequencies where the phase shift approaches 180° . All practical amplifier circuits have phase shifts at high and low frequencies. It is therefore necessary to decrease the open loop gain of the amplifier-transducer system at high and low frequencies.

The back EMF from the speaker is proportional to the velocity of the cone and it, therefore, rises 6 db per octave, as frequency is increased for constant cone displacement. Constant cone displacement will give constant sound output, at the higher frequencies where the radiation efficiency of the speaker is good, and it is, therefore, desirable to cut the back induced voltage by 6 db per octave of frequency increase, so the resultant voltage will be proportional to the displacement of the cone. This voltage is then used as negative feedback, giving cone displacement proportional to input voltage.

If a speaker is connected to a constant voltage source, the back induced voltage rises 6 db per octave as frequency is increased, until it becomes a sizeable portion of the total speaker voltage. Increasing the frequency further causes the back induced voltage to depart from the 6 db rising slope and approach the voltage of the driving source. If the back induced voltage is then cut 6 db per octave of rising frequency, as is done to obtain a voltage proportional to cone displacement, the resultant voltage falls 6 db per octave above the frequency where the back induced voltage departs from the 6 db per octave rising slope. Separation of the back EMF, and a 6 db per octave cut of the back EMF with increasing frequency gives a voltage proportional to the displacement of the

cone that falls 6 db per octave relative to the speaker drive with essentially one 90° phase shift at the high frequencies. This gives an open loop gain, from speaker input to feedback voltage, that falls 6 db per octave with one 90° phase shift. This characteristic is desirable for the design for high frequency stability.

A constant voltage source can be made by placing inverse feedback on the amplifier that supplies the speaker drive.

Maximum sound produced by constant cone displacement occurs in the mid-range and high frequency for most speakers. Below some turn-over frequency the sound produced by constant cone displacement falls at a rate of 12 db per octave. A 6 db boost of the displacement response of the system and a 6 db per octave boost in the drive signal will give a constant sound output below the turn-over frequency. A 6 db per octave boost can be gained by the natural characteristic of the back EMF. Direct application of the back induced voltage will cause speaker displacement to boost 6 db per octave as frequency is decreased. By letting the R-C network used for high frequency compensation become ineffective at lower frequencies, the cone displacement response will rise 6 db per octave at lower frequencies, because the back EMF is being applied directly. Another 6 db per octave boost may be gained, if desired, by another R-C network that reduces the back induced voltage by 6 db per octave before it is used for feedback. This would not be used, however, if large amounts of bass feedback are desired. Instead, a 6 db per octave boost of drive signal would be used. This frequency compensation is shown at 4 in FIG. 1 and at 20 in FIG. 2. The boost of the drive signal is shown at 2 in FIG. 1 and 15 in FIG. 2.

Low frequency phase shifts in conventional amplifier circuits are also a problem. One low frequency phase shift can be cancelled by allowing a phase lag in the response of the amplifier used to cancel the $I \times R$ voltage portion of the speaker voltage (i.e. amplifier 5 in FIG. 1 and amplifier 19 in FIG. 2). Because of the phase inversion in this amplifier and the low level of the back induced voltage at low frequencies, the induced phase lag causes a phase lead in the voltage at the output of amplifier 19 in FIG. 2 and in the output voltage of the summer 3 in FIG. 1, relative to speaker voltage. A phase lag in amplifier 7 or transformer 8 of FIG. 1 can be cancelled, thereby increasing stability or allowing more feedback.

In FIG. 3 the driver is shown at 50 and the speaker or transducer at 52. The driver has one side connected to one side of the speaker coil 54 by return wire 55 and the other side connected to one of the input sides of a voltage summer 56, the output of which is connected to the input of an amplifier 58. The output of the amplifier is supplied to another voltage summer 60, the output of which is supplied to one of the input leads of a frequency compensation component 62. The output of the component 62 is delivered to the input side of amplifier 64. The output side of amplifier 64 supplies primary 66 of a transformer 68, which has a secondary coil 70. One side of coil 70 is connected with the side of speaker coil 54 opposite its connection to driver 50 while the other side of coil 70 is connected through a resistor R2 with driver 50 via return wire 55 and also by a wire 72 with the other input of voltage summer 56.

A wire 74 connects the said one side of secondary 70 with the second input of voltage summer 60.

The circuit of FIG. 3 includes a return wire 55 to which all components are referenced.

Speaker coil 54 has an ohmic resistance equal to R1 and the degree of amplification of amplifier 58 is equal to $R1/R2$ times the losses calculated for voltage summer 56.

The circuit of FIG. 3 represents another way in which the back EMF developed across coil 54 can be fed back into the circuit and applied as negative feedback to coil 54.

The circuit of FIG. 3, similarly to the circuits of FIGS. 1 and 2, includes a frequency compensation component 62 in the circuit between driver 50 and summer 56.

It will be understood that this invention is susceptible to modification in order to adapt it to different usages and conditions; and accordingly, it is desired to comprehend such modifications within this invention as may fall within the scope of the appended claims.

What is claimed is:

1. In a transducer circuit in which drive amplifier means is driven by a source of audio frequency drive voltage and supplies current to a transducer coil immersed in a magnetic field; that method of controlling the motion of the coil in the field which comprises: connecting a single resistor in series with said coil which has a resistance which is a fraction of the ohmic resistance of said coil thereby to develop a first voltage across said resistor which is a fixed predetermined fraction of the IR drop across said coil, amplifying said first voltage at an amplification factor which is the inverse of said fraction and reversing the phase thereof to produce a second voltage which is substantially equal to and in phase opposition with the IR drop across said coil, summing said second voltage with the total voltage drop across said coil to produce a voltage signal which is substantially equal to the back EMF generated in the coil by the motion thereof in said field, and supplying said voltage signal to the input side of said amplifier means as negative feedback.

2. In a transducer circuit: a transducer coil having ohmic resistance R1 and immersed in a magnetic field, a first amplifier having input means and output means, a source of audio frequency drive voltage connected for supplying voltage to said input means of said first amplifier, the output means of said first amplifier being connected to said coil for supplying current thereto to cause movement of the coil in the field, a single resistor connected in series with said coil and having ohmic resistance R2 substantially smaller than R1, means for detecting the total voltage drop across said coil and which voltage drop is substantially equal to the vector sum of the IR drop across the coil and the back EMF induced in said coil due to movement thereof in said field, means for detecting the voltage drop across said resistor, second amplifier means having a gain substantially equal to $R1/R2$ and having input means connected to receive the detected voltage drop across said resistor and having output means at which an amplified voltage is developed which is substantially equal to said IR drop across said coil and substantially in phase opposition therewith, first summing means for summing said detected total voltage drop across said coil and said amplified voltage to form voltage signals substantially equal at any instant to the back EMF induced in said coil due to the motion thereof in said field, and means for supplying said voltage signals to the input means of said first amplifier for negative feedback of said voltage signals to said first amplifier, said last mentioned means comprising second summing means receiving said drive voltage and said voltage signals as inputs and having an output connected to the input means of said first amplifier.

3. A transducer circuit according to claim 2 which includes frequency compensator means through which the output of said second amplifier passes prior to the supply thereof to said first amplifier.

4. A transducer circuit according to claim 3 which includes further frequency compensator means through which the supply from said source of drive voltage passes prior to the supply thereof to said first amplifier.

5. In a transducer circuit: a transducer coil having ohmic resistance R1 and immersed in a magnetic field, a first amplifier having input means and output means, a source of audio frequency drive voltage connected for supplying voltage to said input means of said first amplifier, the output means of said first amplifier being con-

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nected to said coil for supplying current thereto to cause movement of the coil in the field, a single resistor connected in series with said coil and having ohmic resistance R_2 substantially smaller than R_1 , means for detecting the total voltage drop across said coil and which voltage drop is substantially equal to the vector sum of the IR drop across the coil and the back EMF induced in said coil due to movement thereof in said field, means for detecting the voltage drop across said resistor, second amplifier means having a gain substantially equal to R_1/R_2 , a first voltage summer having a first input terminal connected to said source of drive voltage and a second input terminal connected to receive the detected voltage drop across said resistor, said first voltage summer having output terminal means connected to the input means of said second amplifier, and a second voltage summer having a first input terminal connected to the output means of said second amplifier and a second input terminal connected to receive the detected voltage drop across said coil, said second voltage summer having output terminal means connected to the input means of said first amplifier.

6. A transducer circuit according to claim 5 which in-

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cludes frequency compensator means in the circuit connecting the output terminal means of said second voltage summer with the input means of said first amplifier.

7. A transducer circuit according to claim 6 which includes further frequency compensator means in the circuit connecting the said first input terminal of said first voltage summer with said source of drive voltage.

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