The Effect of Negative Voltage Feedback on Power-Supply Hum in Audio-Frequency Amplifiers*

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Summary—Some confusion exists regarding the effect of negative voltage feedback on the signal-to-hum ratio in the output of an audio-frequency amplifier. This appears to be due to lack of care in interpretation of the negative-feedback equations and to the application of these equations to circuit arrangements which do not conform to the conditions implied in their formulation. Various cases are discussed to illustrate the proper interpretation and application of the equations. The conclusions to be derived from these discussions may be summarized briefly as follows:

(1) Where the negative voltage feedback circuits satisfy the relevant conditions implied in the formulation of equations for simple negative feedback, the signal-to-hum ratio, for constant signal output, is improved by the gain-reduction factor $(1-\beta M)$.

(2) This improvement must be interpreted in relation to the complex value of the factor $(1-\beta M)$ and its variation with frequency, in relation to the frequencies of the signal and hum voltages.

(3) Failure to achieve the improvement in signal-to-hum ratio thus predicted may be due to the feedback voltage including voltage other than the fraction β of the output voltage required for simple negative feedback. A further specific analysis is then necessary to determine the effect of the feedback on the signal-to-hum ratio.

(4) In general, hum balancing within the amplifier is independent of the feedback only when the conditions for simple negative feedback are satisfied.

(5) Although, without feedback, it is legitimate to calculate the hum output voltage due to the high-tension hum voltage e by considering simple potential division of this voltage between the load impedance and the valve anode resistance R_a, this procedure is not generally valid when applied to an amplifier with feedback if the effective value of the anode impedance Z_a' of the valve is taken to be $R_a/(1-\mu\beta)$. This arises because Z_a' is the effective value of the valve impedance as viewed from the amplifier output terminals and is not necessarily significant when potential division of the voltage e is considered. It has, however, been shown in Section III(c) that, when the feedback voltage is proportional to $(e+e_0)$, the effect of the feedback on the hum output due to e is identical with that obtained on the basis of simple potential division, using the effective value Z_a'.

I. Introduction

Negative voltage feedback is commonly applied to audio-frequency amplifiers in radio receivers and similar equipment for reduction of nonlinear distortion and frequency discrimination in the amplifier itself or in its load circuit. The theory of negative feedback suggests that hum and other noise voltages introduced by the amplifier and its associated circuits should also be reduced. There is, however, some confusion as to what improvement in signal-to-hum ratio may, in fact, be expected from the application of negative feedback. This appears to arise from two main causes; lack of care in interpretation of the significance of the negative-feedback equations, and application of these equations to circuit arrangements which do not conform to the conditions implied.

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It is the object of the following discussion to clarify these points. The second of them arises from the fact that there is in common use[1–5] a number of negative-feedback circuits that do not conform to the conditions implied in the negative-feedback equations formulated by Black.[6] The term "simple negative feedback" will be used to distinguish circuit arrangements conforming to Black's implied condition that the feedback voltage should be a definite fraction of the output voltage and should not include any other voltages. For simplicity, attention is restricted to the use of negative voltage feedback, and the discussion is illustrated by circuit arrangements typical of its application; but it is obvious that similar considerations might arise in the application of other types of feedback.

The symbols and abbreviations used in the text are summarized below for convenient reference:

M = voltage gain of an amplifier or valve (vacuum tube), measured between the input and output terminals.

M_s = voltage gain from the screen grid to anode of a pentode valve.

μ = amplification factor of the amplifier or valve between input and output terminals.

μ_s = amplification factor of a pentode valve, from screen grid to anode.

β = that fraction of the output voltage fed back to the input circuit of the amplifier.

R_a = alternating-current anode resistance of the output valve of an amplifier.

Z_a = output impedance of the amplifier.

Z = load impedance into which the amplifier works.

e = hum voltage across the output of the high-tension rectifier filter supplying the amplifier.

e_i = an equivalent hum voltage referred to the input terminals of the amplifier and arising from sources within the amplifier *from which the hum is independent of the signal level.*

e_0 = output hum voltage developed across the amplifier output circuit.

e_0' = corresponding output hum voltage when simple

[1] Laboratory staff of Amalgamated Wireless Valve Company, "Negative feedback in R-C amplifiers," *Wirless World*, vol. 43, pp. 437–438; November 17, 1938.

[2] Amalgamated Wireless Valve Company, "Inverse feedback," *Radio Rev. Australia*, vol. 5, p. 64; March, 1937.

[3] G. Robert Mezger, "Feedback amplifier for C.R. oscilloscopes," *Electronics*, vol. 17, pp. 126–131, 254; April, 1944.

[4] F. Langford-Smith, "Radiotron Designer's Handbook," Wireless Press, Sydney, Australia, 1940, pp. 40–45. Complete reproduction, RCA Manufacturing Company, Harrison, N. J.

[5] F. Langford-Smith, "The relationship between the power output stage and the loudspeaker," *Proc. World Radio Convention*, Sydney, Australia, 1938.

[6] H. S. Black, "Stabilized feedback amplifiers," *Bell. Sys. Tech. Jour.*, vol. 13, pp. 1–19; January, 1934.

negative voltage feedback is applied to the amplifier.

e_0'' = corresponding output hum voltage when feedback, other than simple negative feedback, is applied to the amplifier.

In each case, the suffixes t and p are used for amplifiers having the output valve connected as a triode or pentode, respectively.

The amplification factor μ is defined by

$$(de_a/de_g) \text{ for } i_a \text{ constant}$$

where e_a is the anode voltage of the output valve, e_g the potential of the input control grid, and i_a the anode current of the output valve. For a single valve μ is real and negative, in agreement with the actual physical value of the amplification factor. In any case, the sign of μ is consistent with that of M, and in the case of a single valve, corresponds to the change of phase of 180 degrees (for resistive load) between input and output voltages.

II. Simple Negative Voltage Feedback

The general theory and equations of simple negative voltage feedback are well known; but, for clarity, those equations relevant to the discussion will be set out briefly in convenient form. In deriving these equations it is implied that the feedback voltage is derived from, and is directly proportional to, the voltage developed across the amplifier output terminals.

If the voltage gain of an amplifier without feedback is M, and if a *fraction β of the voltage across the output circuit* is fed back to the amplifier input in series with the signal voltage, the gain becomes

$$M' = M/(1 - \beta M) \tag{1}$$

and the quantity $(1-\beta M)$ is conveniently referred to as the gain-reduction factor. The gain M is related to the amplification factor μ of the amplifier, the load Z, and the anode resistance R_a of the output valve, by

$$M = \mu \cdot Z/(Z + R_a). \tag{2}$$

The effect of the feedback on the output impedance of the amplifier is to reduce it, from the anode resistance R_a of the output valve, to a value Z_a' (which will in general have a complex value) given by

$$Z_a' = R_a/(1 - \beta\mu). \tag{3}$$

It is to be noted that μ is always greater than M, and may be much greater when a pentode valve is used, so that the output impedance is reduced by a factor correspondingly greater than the gain-reduction factor.

It can be shown readily that distortion, hum, and noise voltages generated in the amplifier and its associated circuits and *developed across the output circuit* are also reduced by the gain-reduction factor $(1-\beta M)$. When, as is usually the case, the signal input voltage is increased by the factor $(1-\beta M)$ to maintain the signal output at the same level as without feedback, one might expect an improvement in the signal-to-hum and signal-to-distortion ratios across the output circuit by the factor $(1-\beta M)$, insofar as the hum or distortion originates within the amplifier.

These equations are valid for all real and complex values of the parameters μ, M, β, and Z, and the value of the gain reduction factor $(1-\beta M)$ is generally complex and dependent on frequency even for a single-valve amplifier; some of the advantages of negative feedback are in fact due to this.

It is obvious that great care is required to ascertain the exact significance of "an improvement in signal-to-hum ratio by the gain-reduction factor $(1-\beta M)$." An analysis can readily be made for any specific case, and it is clear that the reduction of signal-to-hum ratio must depend on the relative frequencies of the signal and hum voltages; only when the frequencies are identical will the gain-reduction factor be the same for both. It is not unusual to refer to an amplifier having negative feedback giving a gain reduction stated in decibels; the reference is usually to the numerical value of the gain-reduction factor at the center of the transmitted band and the gain-reduction factor at the hum frequency may be very much less, and may even in some cases be less than unity.

Proper application of the theory thus permits a correct assessment of the improvement to be expected in signal-to-hum ratio from the use of negative voltage feedback. Failure to achieve this in practice may be due to the use of feedback circuits that fail to satisfy the conditions implied. One departure from these conditions occurs when the voltage fed back includes voltages other than the fraction β of the amplifier output voltage. In practice, this probably occurs most often if the output valve of the amplifier is transformer-coupled to the load and is series fed, and if the feedback voltage is taken from between anode and cathode of the output valve; the voltage fed back then includes some fraction of any hum voltage in the high-tension supply to the output valve.[1-5]

III. Amplifier with Transformer Coupling to the Load

Transformer coupling is sometimes used for voltage amplification but is chiefly of interest in radio-receiver design for coupling the amplifier power output to a load. For illustration, an amplifier using a series-fed output valve transformer-coupled to the load, and operated under class A conditions, will be considered.

Such an amplifier may use either a pentode or triode output valve. For immediate comparison of the two types it is convenient to consider the same pentode (or beam-power) amplifier valve connected as a triode or pentode. Denoting its anode resistance as a pentode by R_{ap} and as a triode by R_{at}, we have the approximate relation

$$R_{ap} = \mu_s \cdot R_{at} \tag{4}$$

where μ_s is the amplification factor from screen grid to anode. Typical series-fed power-amplifier circuits are shown in Fig. 1. In Fig. 1(a) the output valve is triode-connected and works into a load Z_t presented to it by the output transformer, while in Fig. 1(b), the output valve is pentode-connected and works into a load Z_p. In each case, the anode is fed from a high-tension source with output filter L, C; the impedance of C to hum and signal voltages will be neglected in comparison with the load impedance. Bias arrangements are not shown but are also assumed to have negligible impedance at signal and hum frequencies. Although a single-valve amplifier is depicted in Fig. 1 for purposes of illustration, the ensuing discussion must be taken to be equally applicable to a multistage amplifier.

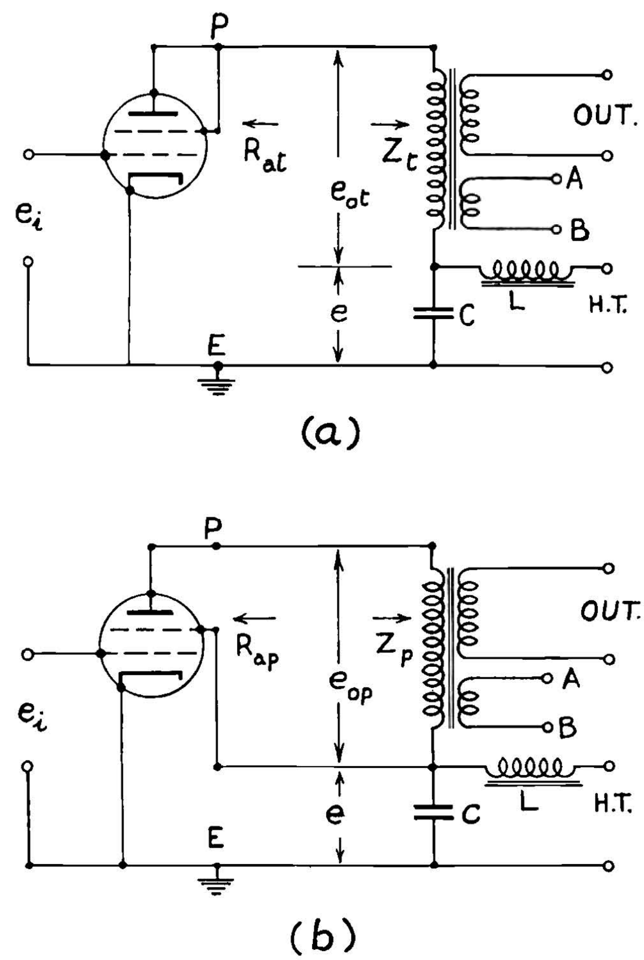

Fig. 1—Series-fed transformer-coupled amplifier (a) triode connection (b) pentode connection.

The hum voltage across the filter capacitor C is denoted by e. Hum arising from other sources within the amplifier is represented by an equivalent hum voltage e_i applied to the input terminals in series with the signal input voltage, and it is assumed that e_i is independent of the signal voltage. It is clear that, should the signal voltage itself include hum voltages, the signal-to-hum ratio in the amplifier output, insofar as it is due to hum from the signal source, will not be affected by the application of negative feedback to the amplifier except insofar as the gain-reduction factor is frequency-dependent and the signal and hum frequencies are different; that is to say, insofar as the frequency-response characteristic of the amplifier is affected by the feedback.

(a) Hum Output Without Feedback

The hum voltage developed across the output circuit is readily calculated. For the triode we have

$$e_{0t} = -Z_t \cdot e/(Z_t + R_{at}) + M_t \cdot e_i \tag{5}$$

where M_t is the voltage gain from grid to anode, and is given by

$$M_t = Z_t \cdot \mu_t/(Z_t + R_{at}).$$

The first term of (5) corresponds to simple potential division of the hum voltage e between the load and anode impedances, while the second represents the amplification of the equivalent hum voltage e_i referred to the amplifier input circuit.

For the pentode, account must also be taken of the hum voltage e applied to the screen grid, and the output ripple voltage is given by

$$e_{0p} = -Z_p \cdot e/(Z_p + R_{ap}) + M_s \cdot e + M_p \cdot e_i \tag{6}$$

where M_p is the voltage gain from grid to anode and M_s that from screen grid to anode, and

$$M_p = Z_p \cdot \mu_p/(Z_p + R_{ap}) \qquad M_s = Z_p \cdot \mu_s/(Z_p + R_{ap}).$$

Comparison of (5) and (6), taking into account (4), indicates that the hum output voltage for a pentode, arising from the hum voltage e applied to its anode and screen circuits, will usually exceed the corresponding output hum voltage for the triode owing to the magnitude of the term $M_s e$. For example, the beam-power valve type 6V6G has the typical operating conditions.

$R_{at} = 2500$ ohms	$R_{ap} = 50,000$ ohms
$Z_t = 4000$ ohms	$Z_p = 5000$ ohms
$\mu_s = -20$	$M_s = -1.8$

and (5) and (6) give the respective hum output voltages

$$e_{0t} = -0.6e \qquad e_{0p} = -1.7e.$$

Such a comparison will, of course, apply only when series feed is used and the screen supply includes the hum voltage e. If the screen supply is further filtered to such an extent that the hum voltage applied to the screen is negligible, the output hum voltage due to e is determined by the first term of (6) and will be considerably less than in the case of the triode, owing to the large value of the anode resistance R_{ap} in comparison with the load impedance.

(b) The Effect of Simple Negative Feedback on the Hum Output Voltage

The application of simple negative voltage feedback to the amplifier, as defined in Section II, requires that the voltage fed back be a fraction of the voltage developed across the output load circuit; i.e., across Z_t or Z_p. This condition is most readily satisfied by taking the feedback voltage across an appropriate winding AB on the output transformer as indicated in

Fig. 1. When this is done, the hum output voltage is reduced by the factor $(1-\beta M)$. We then have, for the triode and pentode connections, respectively,

$$e_{0t}' = e_{0t}/(1 - \beta M_t) \tag{7}$$

$$e_{0p}' = e_{0p}/(1 - \beta M_p). \tag{8}$$

These expressions cannot be formulated in terms of the reduction in effective output impedance Z_a' of the amplifier because the voltage e is not included in the feedback and the effective output impedance Z_a' is not applicable to such a calculation; i.e., it is not the effective impedance as viewed from the terminals of the voltage e.

It is obvious that, in this case, the reduction in the hum output voltages occurs equally for hum from the various sources and any hum balancing within the amplifier will not be affected by the feedback. However, if the output transformer feeds a moving-coil loudspeaker of which the field coil is used for smoothing the rectified high-tension supply to the amplifier, the speaker may have a hum-balancing coil wound over the field coil and connected in series with the voice coil. In general, a hum voltage will then be produced across the transformer secondary and reduction of this voltage by the feedback may require compensation by adjustment of the hum-balancing coil.

(c) *The Effect of Other Feedback Circuits on the Hum Output Voltage*

It is a common, and undoubtedly convenient, practice to utilize a feedback voltage other than that required for simple negative feedback as specified in Section II above. Among the most common of such modified circuits is that in which the feedback voltage is obtained by potential division from the anode-cathode voltage of the output amplifier; i.e., the voltage between points P and E in Figs. 1(a) and 1(b). This arrangement departs from the simple feedback circuit in that the feedback voltage is a fraction, not of the output load voltage, but of the output voltage plus the hum voltage e across the capacitor C. It is not, therefore, to be expected that the modification of the hum output voltage indicated by the theory of simple feedback will occur.

If the output valve is triode-connected, the effect of this feedback circuit will be to change the output hum voltage from its value e_{0t} without feedback (equation (5)), to a value e_{0t}'' given by

$$e_{0t}'' = -Z_t \cdot e/(Z_t + Z_{at}') + M_t' \cdot e_i \tag{9}$$

where

$$Z_{at}' = R_{at}/(1 - \beta\mu_t).$$
$$M_t' = M_t/(1 - \beta M_t)$$

and for large amounts of feedback this approximates to

$$e_{0t}'' = -e + M_t' \cdot e_i \tag{10}$$

indicating that, owing to the reduction in the effective output impedance of the amplifier by the feedback, practically the whole of the hum voltage e is developed across the load; but that hum voltages represented by e_i are reduced by the gain-reduction factor. It happens in this case, because the feedback voltage is proportional to $(e+e_0)$, that the effect of the feedback on the hum due to e can be expressed in terms of the change in effective output impedance of the amplifier.

If the output valve is pentode connected, the effect of this feedback arrangement will be to change the hum voltage output from its value e_{0p} without feedback, as given in (6), to a value e_{0p}'' given by

$$e_{0p}'' = -Z_p \cdot e/(Z_p + Z_{ap}') + M_s' \cdot e + M_p' \cdot e_i \tag{11}$$

where

$$Z_{ap}' = R_{ap}/(1 - \beta\mu_p)$$
$$M_s' = M_s/(1 - \beta M_p)$$
$$M_p' = M_p/(1 - \beta M_p).$$

Without feedback, the first term of (11) is small but increases to the limiting value $-e$ for large values of feedback, as in the case of the triode. The hum arising in the screen and input circuits is decreased by the gain-reduction factor.

(d) *Hum Balancing*

For either connection of the output valve, the net result of the feedback on the total output hum depends on the relative phases and amplitudes of the various hum voltages. Equations (5), (6), (9), and (11) state the conditions necessary for reduction of the output hum voltage to zero by any process of hum-balancing within the amplifier such as those described[7,8] in the literature. It is to be noted that any such balance generally depends on the degree and nature of the feedback, but that *when the conditions for simple negative feedback are satisfied, the balance is independent of the feedback*, as indicated by the form of (7) and (8).

IV. Other Amplifiers

In amplifiers having an output circuit other than the series-fed transformer arrangement discussed in relation to Fig. 1, the output voltage is usually identical with the anode-to-cathode voltage of the output valve, and the relevant conditions for simple negative feedback are satisfied by almost any convenient circuit arrangement. This applies, for example, to a parallel-fed transformer-coupled output circuit, or to a resistance- or choke-coupled voltage amplifier. Simplified circuits corresponding to these cases are shown in Figs. 2(a) and 2(b) and can be used to represent a wide range of practical cases.

In Fig. 2 the high-tension supply is fed to the amplifier anode through an impedance Z_1 which may be a

[7] Wen-Yuan Pan, "Circuit for neutralizing low-frequency regeneration and power-supply hum," Proc. I.R.E., vol. 30, pp. 411–412; September, 1942.

[8] K. B. Gonser, "A method of neutralizing hum and feedback caused by variations in the plate supply," Proc. I.R.E., vol. 26, pp. 442–449; April, 1938.

resistance (e.g., resistance-capacitance-coupled voltage amplifier) or a choke (e.g., parallel-fed transformer-coupled amplifier). The anode of the valve is coupled through a blocking capacitor to a load Z_2 which may be the grid leak of a succeeding stage, or may be presented

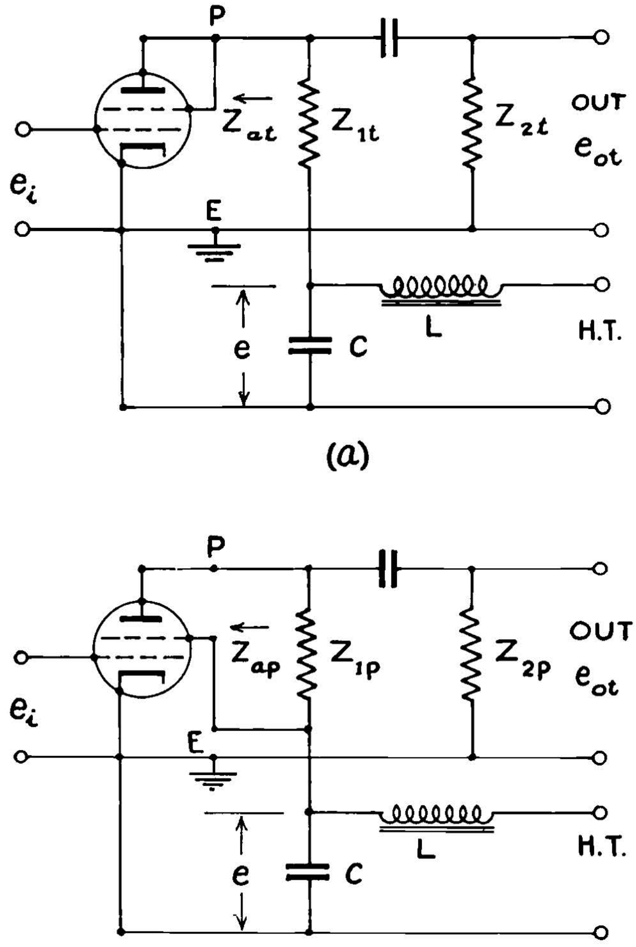

Fig. 2—Parallel-fed amplifier (a) triode connection (b) pentode connection.

by the primary of an output transformer. In Fig. 2(a) the output valve is triode-connected, and in Fig. 2(b), pentode-connected. In each case the hum and signal voltages applied are the same as in the foregoing discussion.

Without feedback, the hum output voltage may readily be shown to be, for the triode and pentode connections respectively,

$$e_{0t}=\frac{-R_{at}\cdot Z_{2t}}{R_{at}\cdot Z_{2t}+R_{at}Z_{1t}+Z_{1t}\cdot Z_{2t}}\cdot e+M_t\cdot e_i \qquad (12a)$$

$$e_{0p}=\frac{-R_{ap}\cdot Z_{2p}}{R_{ap}\cdot Z_{2p}+R_{ap}\cdot Z_{1p}+Z_{1p}\cdot Z_{2p}}\cdot e+M_s\cdot e+M_p\cdot e_i \qquad (12b)$$

where

$$Z = Z_1\cdot Z_2/(Z_1 + Z_2)$$
$$M = Z\cdot \mu/(Z + R_a)$$
$$M_s = Z\cdot \mu_s/(Z + R_a)$$

and the subscripts t and p refer to the triode and pentode connection respectively. Z, M, and M_s have the same significance as in the cases discussed previously. In (12a) and (12b) the first term represents simple potential division of the hum voltage e between the feed impedance Z_1 and the load Z_2 in parallel with the anode resistance R_a of the valve. It is clear that the hum output voltage will, in general, in the case of parallel feed be less for a triode, but greater for a pentode, than in the case of series feed.

Negative voltage feedback may be provided by simple potential division of the anode-cathode voltage of the valve or from a winding on an output transformer. In any straightforward method, the feedback voltage will be proportional to the amplifier output voltage, because this is identical with the anode-cathode voltage and the conditions for ***simple negative feedback*** are satisfied. The effect of the negative voltage feedback is, therefore, to reduce the hum output voltage from all sources by the gain-reduction factor. As in the case discussed in Section III(b) above, the effect of the feedback on the hum output voltage due to e, as given by the first term of (12), cannot be formulated in terms of the change in effective output impedance Z_a' of the amplifier with feedback, because the impedance Z_a' is the effective output impedance viewed from the output terminals and is not significant for the purpose of considering potential division of the hum voltage e.

Because the feedback satisfies our definition of ***simple negative feedback***, hum-balancing arrangements within the amplifier are unaffected by the feedback. Hum across the load due to a loudspeaker hum-balancing coil can be treated as part of the hum output voltage Me_i and is reduced by the gain-reduction factor; some readjustment of the hum-balancing arrangement in the loudspeaker will be necessary.

V. Acknowledgment

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