Vented-Box Loudspeaker Systems Part III: Synthesis

RICHARD H. SMALL

School of Electrical Engineering, The University of Sydney, Sydney, N.S.W. 2006, Australia

The analytical relationships developed in Parts I and II which relate the performance characteristics of the vented-box loudspeaker system to the basic parameters of its components make possible the straightforward design of loudspeaker systems meeting specific performance goals. A set of desired system performance specifications may be checked for realizability and then used to determine the required physical properties of all the system components. The most suitable enclosure design for a particular driver may also be readily determined.

Editor's Note: Part I of Vented-Box Loudspeaker Systems appeared in the June issue and Part II in July/August.

11. SYSTEM SYNTHESIS

System-Component Relationships

The relationships between response and system parameter adjustment are given in Part I by Figs. 6 and 9–13 for the "flat" C4–B4–QB3 alignments. Enclosure losses cannot be known exactly in advance but can be predicted from experience. For example, for numerous commercial systems and laboratory enclosures in the range of 25–100 dm^3 (1–4 ft^3) measured in the course of this research, the most commonly measured values of Q_B are between 5 and 10 with a general tendency for Q_B to fall with increasing enclosure volume.

For enclosures of moderate size, the assumption of an equivalent Q_L value of 7 is a very satisfactory starting point for design purposes. In this case Fig. 11 is used to represent the basic relationships between driver parameters, system parameters, and system response. If a higher or lower value of Q_B is expected with some confidence, one of the other figures is used.

The appropriate alignment and response relationships (Fig. 11 or otherwise) and the efficiency, power capacity, and vent design relationships established in Parts I and II permit the design of vented-box systems in complete detail. Procedures are described and illustrated below for two important cases, design of an enclosure to suit a particular driver and design of a complete system starting from required performance specifications.

Design with a Given Driver

The design of an enclosure to suit a given driver

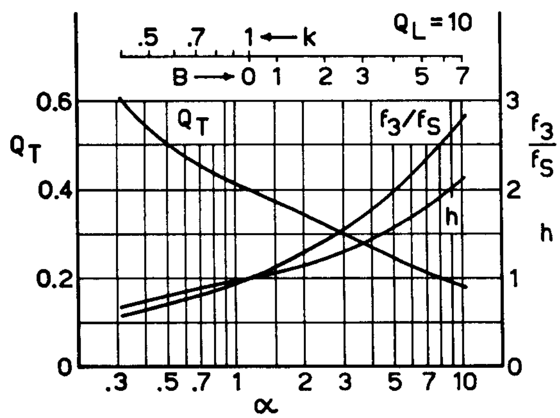

Fig. 10. Alignment chart for vented-box systems with $Q_B = Q_L = 10$.

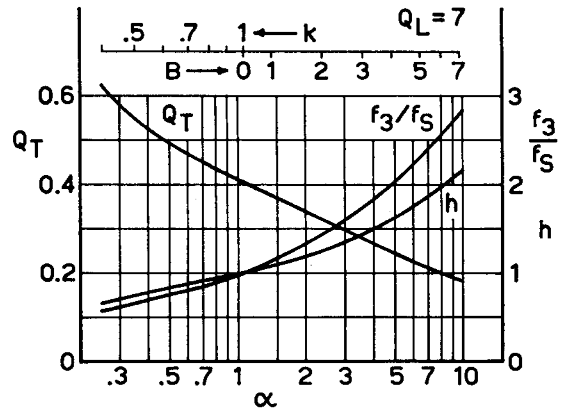

Fig. 11. Alignment chart for vented-box systems with $Q_B = Q_L = 7$.

starts with a knowledge of the driver small-signal parameters f_S, Q_{TS}, and V_{AS}; f_S and Q_{TS} must be adjusted if necessary to correspond to enclosure mounting conditions. If these parameters are not already known, they may be measured by the methods given in [10] or [12] using a standard baffle to provide air-mass loading as for an enclosure (see also Section 7 in Part II of the present paper, including Footnote 3).

The value of Q_{TS} is of primary importance. If the loudspeaker system is to be used with a modern amplifier having very low output (Thevenin) resistance, then Q_T for the system will be equal to Q_{TS} for the driver. From Figs. 6 and 9–13 it is clear that Q_T must be no larger than about 0.6 for successful application in a vented enclosure.

If Q_{TS} has a reasonable value, then the optimum value of α for a system using the driver is found from, say, Fig. 11 by locating the measured value of Q_{TS} on the Q_T curve in the figure and observing the corresponding value of α on the abscissa. This value of α then determines the optimum value of V_B using Eq. (46). It also determines the required value of h (and therefore f_B) and the corresponding value of f_3 for the system as indicated on the same figure. If the resulting system design is not acceptable (f_3 too high, V_B too large, etc.), then it is probable that the driver is not suitable for use in a vented-box system.

The design process may alternatively be begun by selecting an enclosure size V_B which suits aesthetic or architectural requirements. This determines α and hence the required enclosure tuning f_B, the required value of Q_T, and the resulting cutoff frequency f_3. If the value of f_3 is not satisfactory, then the driver and the enclosure size chosen are not compatible. If f_3 is satisfactory but the required Q_T is very different from Q_{TS}, it may be possible to use the driver as discussed below.

There are limited ways of salvaging a driver having unsatisfactory parameter values. If the value of Q_{TS} is too high to fit an alignment which is otherwise desirable in terms of enclosure size and bandwidth, an acoustically resistive material such as bonded acetate fiber may be stretched over the rear of the driver frame to reduce the effective value of Q_{MS}, thus lowering Q_{TS} [17], [27]. The correct amount of resistive material is determined experimentally by remeasurement of Q_{TS} as material is added. Q_T may also be reduced by using a negative value of amplifier output resistance R_g [10, Sec. 12], [28] to produce a low value of Q_E, where [12, eq. (21)]

$$Q_E = Q_{ES}\frac{R_g + R_E}{R_E} \tag{53}$$

because in this case [12, eq. (22)]

$$Q_T = Q_E Q_{MS}/(Q_E + Q_{MS}). \tag{54}$$

Both methods reduce Q_T without changing Q_{ES}; thus the value of $k_{\eta(Q)}$ from Eq. (29), and therefore η_0 for the system, will be lower than could be achieved by altering the magnet design to reduce Q_{ES} directly.

Sometimes the value of Q_{TS} is found to be undesirably low. This may be remedied by placing a resistor in series with the voice coil to increase R_E and therefore Q_{ES} or by using a positive value of R_g to increase Q_E.

If the driver proves satisfactory and an acceptable system design is found, the system reference efficiency is calculated from the basic driver parameters using Eq. (25). The approximate displacement-limited acoustic power rating of the system is computed from Eq. (41) if V_D is known. V_D usually can be evaluated as described in [22, Sec. 6]. The approximate displacement-limited input power rating is then found by dividing the acoustic power rating by the reference efficiency as indicated by Eq. (42). The vent design is carried out in accordance with Section 8 of Part II.

Example of Design with a Given Driver

The following small-signal parameters were measured for an 8-inch wide-range driver manufactured in the United States:

$$f_S = 33 \text{ Hz}$$

$$Q_{MS} = 2.0$$

$$Q_{ES} = 0.45$$

$$V_{AS} = 57 \text{ dm}^3 \text{ (2 ft}^3\text{)}.$$

The large-signal characteristics specified by the manufacturer are as follows.

1) "Total linear excursion of one-half inch." From this, $x_{\max} = 6$ mm, and, assuming a typical effective diaphragm radius of 0.08 m,

$$V_D = 120 \text{ cm}^3.$$

2) "Power capacity 25 watts program material." From this it is assumed that for program material the thermal capacity of the driver is adequate for operation with amplifiers of up to 25-watt continuous rating.

By calculation from Eqs. (31) and (25).

$$Q_{TS} = 0.37$$
$$\eta_0 = 0.44\% .$$

Assuming that the amplifier to be used with the system has negligible Thevenin output resistance, Q_T for the system will be 0.37. Taking $Q_B = 7$ initially, Fig. 11 indicates that the enclosure volume will be relatively small; a more likely value of Q_B is thus about 10. Using Fig. 10 then, a QB3 response with $B = 1.0$ can be obtained for which the system parameters are

$$\alpha = 1.55$$
$$h = 1.07$$
$$f_3/f_S = 1.16.$$

Thus the required enclosure volume is

$$V_B = V_{AS}/\alpha = 37\ \text{dm}^3\ (1.3\ \text{ft}^3).$$

The enclosure must be tuned to

$$f_B = hf_S = 35\ \text{Hz}$$

and the system cutoff frequency is

$$f_3 = 38\ \text{Hz}.$$

From Eq. (41) the displacement-limited program acoustic power rating of the system is

$$P_{AR} = 3.0\, f_3{}^4\, V_D{}^2 = 90\ \text{mW}.$$

The corresponding displacement-limited program input power rating is

$$P_{ER} = P_{AR}/\eta_0 = 20\ \text{W}.$$

Because this is less than the manufacturer's input power rating, it should be quite safe to operate the system with an amplifier having a continuous power rating of 20 watts.

From Eq. (52) the minimum diameter of a tubular vent is $(V_D f_B)^{1/2}$ or 65 mm (2.6 inches). From Fig. 21, the required vent length is 175 mm (7 inches) for a tubing of this diameter.

Design from Specfications

The important performance specifications of a loudspeaker system include frequency response, efficiency, power capacity, and enclosure size. The complexity of the vented-box system makes control of all these specifications quite difficult when traditional trial-and-error design techniques are used. In contrast, the analytical relationships developed in this paper make possible the direct synthesis of a vented-box system to meet any physically realizable set of small-signal and large-signal specifications and even provide a check on realizability before design is begun.[4]

Specification of system frequency response basically amounts to specification of an alignment type and a cutoff frequency f_3. While the emphasis in this paper is on the "flat" C4–B4–QB3 alignments, any other desired alignment may be specified, e.g., the degenerated Chebyshev type 2 (DT2) alignment used by Nomura which provides passband peaking [11]. Appendix 1 shows how the required system alignment parameters may be calculated from the polynomial coefficients of any desired alignment based on the assumed or expected value of Q_B. For any alignment in the C4–B4–QB3 range, the necessary alignment data are provided in Figs. 9–13. The frequency response specification thus fixes the values of the parameters α, Q_T, f_S, and f_B.

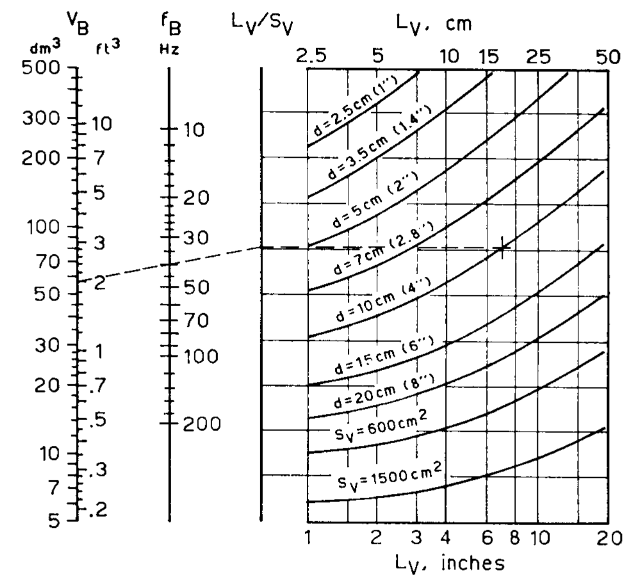

Fig. 21. Nomogram and chart for design of ducted vents.

For a specified frequency response, the designer may specify also the enclosure size or the reference efficiency; but he may not specify both unless the values satisfy the realizability requirements of Section 4. If the enclosure volume V_B is specified, the required driver compliance is then

$$V_{AS} = \alpha V_B. \qquad (46)$$

The required value of the driver parameter Q_{ES} is found from the required value of Q_T by allowing for reasonable values of R_g (typically zero) and Q_{MS} (typically 5, but varies greatly depending on the amount of mechanical damping deliberately added to the suspension to suppress higher frequency resonances). The system efficiency is then calculated from Eq. (25).

The power capacity of the system may be specified in terms of either P_{ER} or P_{AR}, but not both unless the values agree with the attainable system efficiency. It is possible to specify both independently only if neither V_B nor η_0 are separately specified; then the required value of η_0 is given by the ratio of P_{AR} to P_{ER}, and the required enclosure volume which will provide this efficiency for the specified frequency response is found from Eqs. (26) and (28) using values of $k_{\eta(Q)}$ and $k_{\eta(G)}$ obtained from Eq. (32) and Fig. 15 and based on the estimated or expected values of Q_{MS} and Q_B.

Assuming that V_B and P_{AR} are specified and that η_0 has been determined from Eq. (25), P_{ER} is given by

$$P_{ER} = P_{AR}/\eta_0. \qquad (42)$$

The required value of V_D for the driver is found from

[4] See [32, Sec. 5 and 6] for an extensive discussion of the principles of system small-signal response synthesis.

Eq. (41) using the given values of f_3 and P_{AR}. Check that $V_D << V_B$. The thermally limited maximum input power rating of the driver $P_{E(\max)}$ must be not less than the value of P_{ER} divided by the peak-to-average power ratio of the program material to be reproduced.

The vent is designed so that the area S_V satisfies Eq. (51) and the effective length-to-area ratio gives the required f_B in combination with the enclosure volume V_B as determined from Fig. 21.

The driver is completely specified by the parameters calculated above and may be designed by the method given in Section 12.

Example of System Design from Specifications

A loudspeaker system to be used with an amplifier having very low output resistance must meet the following specifications:

$$\begin{aligned} f_3 &= 40 \text{ Hz} \\ \text{Response} &= \text{B4} \\ V_B &= 57 \text{ dm}^3 \text{ (2 ft}^3\text{)} \\ P_{AR} &= 0.25 \text{ W program peaks; expected peak-} \\ &\quad\ \text{to-average power ratio 5 dB.} \end{aligned}$$

It is assumed that the enclosure losses will correspond to $Q_B = Q_L = 7$ and that the driver mechanical losses will correspond to $Q_{MS} = 5$.

Using Fig. 11, the B4 response is located at a compliance ratio of

$$a = 1.06$$

for which the required system parameters are

$$\begin{aligned} h &= 1.00 \\ f_3/f_S &= 1.00 \\ Q_T &= 0.40. \end{aligned}$$

Therefore the required driver parameters are

$$\begin{aligned} V_{AS} &= 60 \text{ dm}^3 \text{ (2.1 ft}^3\text{)} \\ f_S &= 40 \text{ Hz} \\ Q_{TS} &= 0.40 \end{aligned}$$

and the required enclosure tuning is

$$f_B = 40 \text{ Hz}.$$

Taking $Q_{MS} = 5$ and using Eq. (31),

$$Q_{ES} = 0.44.$$

From Eq. (25) the reference efficiency of the system is then

$$\eta_0 = 0.84\%$$

and from Eq. (42) the displacement-limited electrical power rating is

$$P_{ER} = 30 \text{ W}.$$

This requires that the system amplifier have a continuous power rating of at least 30 watts. For the 5-dB expected peak-to-average power ratio of the program material, the thermal rating $P_{E(\max)}$ of the driver must be at least 9.5 watts [22, Sec. 5].

From Eq. (41), the displacement volume of the driver must be

$$V_D = 180 \text{ cm}^3.$$

This is only about 0.3% of V_B. Then, from Eq. (52), a tubular vent should be at least 85 mm (3.4 inches) in diameter. From Fig. 21, the length should be 115 mm (4.5 inches) for a tubing of this diameter.

12. DRIVER DESIGN

Driver Specification

The process of system design leads to specification of the required driver in terms of the basic design parameters f_S, Q_{ES}, V_{AS}, V_D, and $P_{E(\max)}$. To complete the physical specification of the driver, the arbitrary physical parameters S_D and R_E must be selected and the resulting mechanical parameters calculated. This process is described in [22, Sec. 10] and is illustrated by the example below.

Example of Driver Design

The basic design parameters of the driver required for the system in the example of the previous section are

$$\begin{aligned} f_S &= 40 \text{ Hz} \\ Q_{ES} &= 0.44 \\ V_{AS} &= 60 \text{ dm}^3 \\ V_D &= 180 \text{ cm}^3 \\ P_{E(\max)} &= 9.5 \text{ W}. \end{aligned}$$

These specifications could be met by drivers of 8–15-inch advertized diameter [15].

Choosing a 12-inch driver, the effective diaphragm radius a will be approximately 0.12 m, giving

$$S_D = 4.5 \times 10^{-2} \text{ m}^2$$

and

$$S_D{}^2 = 2.0 \times 10^{-3} \text{ m}^4.$$

The required mechanical compliance and mass of the driver are then [22, eqs. (61) and (62)]

$$\begin{aligned} C_{MS} &= V_{AS}/(\rho_0 c^2 S_D{}^2) = 2.14 \times 10^{-4} \text{ m/N} \\ M_{MS} &= 1/[(2\pi f_S)^2 C_{MS}] = 74 \text{ g}. \end{aligned}$$

M_{MS} is the total moving mass including air loads. Assuming that the driver diaphragm occupies one third of the area of the front baffle of the enclosure and using [3, pp. 216-217] to evaluate the air loads, the mass of the voice coil and diaphragm alone is

$$M_{MD} = M_{MS} - (3.15a^3 + 0.65\pi\rho_0 a^3) = 64 \text{ g}.$$

The electromechanical damping resistance must be [22, eq. (64)]

$$B^2l^2/R_E = 2\pi f_S M_{MS}/Q_{ES} = 42 \text{ N}\cdot\text{s/m}.$$

For the popular 8Ω rating impedance, R_E is usually about 6.5 Ω. The required Bl product for such a driver is then

$$Bl = 16.5 \text{ T}\cdot\text{m}.$$

For the required displacement volume of 180 cm^3, the peak linear displacement of the driver must be

$$x_{\max} = V_D/S_D = 4.0 \text{ mm}.$$

This is approximately the amount of voice-coil overhang required at each end of the magnetic gap. The total "throw" of the driver is then 8.0 mm (0.32 inch). This requirement presents no great difficulty so far as the design of the suspension is concerned.

The choice of a smaller driver diameter results in a lighter diaphragm and a less costly magnetic structure, but a greater peak displacement is then required, e.g., 9 mm (18-mm total throw) for an 8-inch driver.

The voice coil must be able to dissipate 9.5 watts nominal input power without damage.

13. DESIGN VERIFICATION

The suitability of a prototype driver designed in accordance with the above method may be checked by measuring the driver parameters as described in [12].

One of the driver parameters which is difficult to control in production is the mechanical compliance C_{MS}. Any shift in this compliance changes the measured values of both f_S and Q_{ES} as well as V_{AS}. Fortunately, system response is not critically sensitive to the value of C_{MS} so long as M_{MS} and B^2l^2/R_E have the correct values. Thus if the measured value of V_{AS} is not too far off its specified value, the driver will be satisfactory provided the quantities $f_S{}^2V_{AS}$ and f_S/Q_{ES}, which together indicate the effective moving mass and magnetic coupling, correspond to the same combinations of the specified parameters.

The effect of variations in C_{MS} on the response of a vented-box system is shown in Fig. 23 for a B4 alignment. The $\pm 50\%$ variation illustrated is larger than that commonly encountered. The relative effects are smaller for higher compliance ratios (i.e., QB3 alignments) and larger for lower compliance ratios (C4 alignments).[5]

The completed system may be checked by measuring its parameters as described in Section 7 and comparing these to the initial specifications. The actual system performance may also be verified by measurement in an anechoic environment or by an indirect method [26].

14. SPECIFICATIONS AND RATINGS

Drivers

The moving-coil or electrodynamic driver has long been the workhorse of the loudspeaker industry. However, system designers have not been fully aware of the importance or usefulness of a knowledge of the important fundamental parameters of these drivers. They have instead used trial-and-error design techniques and relied on acoustical measurements of a completed system to determine the performance characteristics of the system.

The most important message of this paper and those that have preceded it is that trial-and-error design techniques are not only wasteful but unnecessary. Design may be carried out by direct synthesis provided the system designer either knows the parameters of a given driver or can obtain a desired driver by specifying its parameters.

It is essential for a driver manufacturer to specify all the important parameters of a driver so that system designers can completely evaluate the small-signal and large-signal performance obtainable from that driver. In addition to the specific physical properties of diaphragm

[5] A very recent paper by Keele [33] contains exact calculations of the sensitivity factors of vented-box alignments to all important driver and system parameters. The sensitivity to driver compliance is shown to be extremely low compared to that for most other parameters over a wide range of alignments.

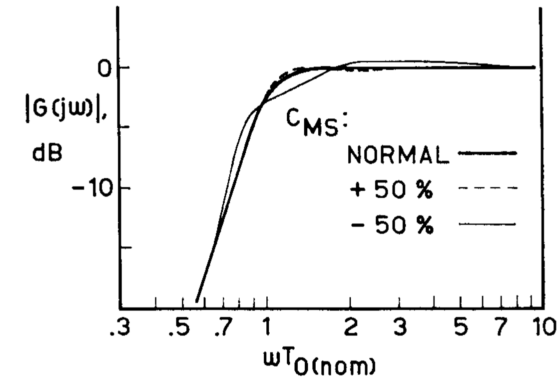

Fig. 23. Variation in frequency response of a B4-aligned vented-box system for changes in driver compliance C_{MS} of $\pm 50\%$ (from simulator).

size and voice-coil resistance (or rating impedance), the designer needs to know the values of the parameters f_S, Q_{ES}, Q_{MS}, V_{AS}, V_D, and $P_{E(\max)}$. Conversely, where the designer needs a driver having particular values of these parameters, the driver manufacturer must be able to work from such specifications to produce the driver.

Because the basic design parameters above are directly related to the fundamental mechanical parameters such as M_{MD}, C_{MS}, B, and l, which the driver manufacturer has long used, there need be no difficulty in supplying these parameters. There is every likelihood that feedback from system designers will be helpful to driver manufacturers in improving their products, particularly in finding the best tradeoffs among response, efficiency, and power capacity requirements which can be obtained for a given cost.

Systems

Because the frequency response, reference efficiency, and displacement-limited power capacity of a vented-box loudspeaker system are all directly related to a relatively small number of easily measured system and driver parameters, there is every incentive for system manufacturers to provide complete data on these fundamental performance characteristics with the basic system specifications.

The theoretical relationships developed here refer to a standard radiation load of a 2π-steradian free field. This is only an approximation to average listening-room conditions [29], but ratings and specifications based on these relationships are of unquestionable value in comparing the expected performance of different systems in a particular application.

There is little doubt that buyers and users of loudspeaker systems would appreciate an increase in the amount of quantitative and directly comparable data supplied with such systems, especially in the categories of reference efficiency and acoustic power capacity.

15. CONCLUSION

The vented-box loudspeaker system has been popular for decades but has recently been shunned in favor of the more easily designed closed-box system.

The quantitative relationships presented in this paper make the design of vented-box systems a relatively simple task, despite the complexity of these systems.

They also indicate that the vented-box system has substantial advantages over the closed-box system in terms of the attainable values of the efficiency and power-rating constants, although these advantages are gained at the expense of transient response and immunity to subsonic signals.

As the design of vented-box systems becomes better understood, interest in these systems may be expected to increase again. This does not mean that the popularity of well-designed closed-box systems will diminish. The choice of one or the other will depend on the requirements of a particular application.

The ease with which the low-frequency performance of a loudspeaker system may be specified in terms of simply measured system parameters should encourage more complete specification by manufacturers of the important frequency response, reference efficiency, and power capacity characteristics of their products.

16. ACKNOWLEDGMENT

This paper is part of the result of a program of postgraduate research into the low-frequency performance of direct-radiator electrodynamic loudspeaker systems. I am indebted to the School of Electrical Engineering of the University of Sydney for providing research facilities, supervision, and assistance, and to the Australian Commonwealth Department of Education and Science for financial support.

My indebtedness to A. N. Thiele for the inspiration behind the research program has already been acknowledged. We are also grateful for his considerable encouragement, helpful suggestions, and valuable criticisms of techniques and results.

I am further indebted to J. E. Benson for his generous assistance in discussing the subject matter of this paper and in examining and criticizing early manuscripts, and to Dr. R. H. Frater for his valuable contributions to the organization of this paper.

Finally, I acknowledge with gratitude the generous and considerable efforts of R. C. Pols in providing an English translation of the van Leeuwen paper.

REFERENCES

[3] L. L. Beranek, *Acoustics* (McGraw-Hill, New York, 1954).

[10] A. N. Thiele, "Loudspeakers in Vented Boxes," *Proc. IREE (Australia)*, vol. 22, p. 487 (Aug. 1961); republished in *J. Audio Eng. Soc.*, vol. 19, p. 382 (May 1971), and p. 471 (June 1971).

[11] Y. Nomura, "An Analysis of Design Conditions of a Bass-Reflex Loudspeaker Enclosure for Flat Response," *Electron. Commun. Japan*, vol. 52-A, no. 10, p. 1 (1969).

[12] R. H. Small, "Direct-Radiator Loudspeaker System Analysis," *IEEE Trans. Audio Electroacoust.*, vol. AU-19, p. 269 (Dec. 1971); republished in *J. Audio Eng. Soc.*, vol. 20, p. 383 (June 1972).

[15] J. R. Ashley and M. D. Swan, "Improved Measurement of Loudspeaker Driver Parameters," presented at the 40th Convention of the Audio Engineering Society, Los Angeles (Apr. 1971). Preprint 803.

[17] J. F. Novak, "Designing a Ducted-Port Bass-Reflex Enclosure," *Electron. World*, vol. 75, p. 25 (Jan. 1966).

[22] R. H. Small, "Closed-Box Loudspeaker Systems," *J. Audio Eng. Soc.*, vol. 20, p. 798 (Dec. 1972); vol. 21, p. 11 (Jan./Feb. 1973).

[26] R. H. Small, "Simplified Loudspeaker Measurements at Low Frequencies," *Proc. IREE (Australia)*, vol. 32, p. 299 (Aug. 1971); republished in *J. Audio Eng. Soc.*, vol. 20, p. 28 (Jan./Feb. 1972).

[27] J. L. Grauer, "Acoustic Resistance Damping for Loudspeakers," *Audio*, vol. 49, p. 22 (Mar. 1965).

[28] W. Steiger, "Transistor Power Amplifiers with Negative Output Impedance," *IRE Trans. Audio*, vol. AU-8, p. 195 (Nov./Dec. 1960).

[29] R. F. Allison and R. Berkovitz, "The Sound Field in Home Listening Rooms," *J. Audio Eng. Soc.*, vol. 20, p. 459 (July/Aug. 1972).

[32] J. E. Benson, "Theory and Design of Loudspeaker Enclosures, Part 3—Introduction to Synthesis of Vented Systems," *A.W.A. Tech. Rev.*, vol. 14, p. 369 (Nov. 1972).

[33] D. B. Keele, Jr., "Sensitivity of Thiele's Vented Loudspeaker Enclosure Alignments to Parameter Variations," *J. Audio Eng. Soc.*, vol. 21, p. 246 (May 1973).