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AES Information Document — Plane-Wave Tubes: Design and Practice

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Abstract
The "AES Recommended Practice — Specification of Loudspeaker Components Used in Professional Audio and Sound Reinforcement" in its 2.2.1 calls for the use of plane-wave tube measurement of horn drivers. Because many variations and results are possible, depending on the details of construction of plane-wave tubes, this document discusses those variations for the purpose of encouraging further experimentation.

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[This foreword is not a part of *AES information document — plane-wave tubes: design and practice,* AES 1id-1991.]

Foreword

An Audio Engineering Society information document is, according to the *Operating Policy of the Audio Engineering Society Standards Committee*, "a summary of scientific and technical information, originated by a technically competent writing group, important to the preparation and justification of a standard or to the understanding and application of such information to a specific technical subject . . . ." The AES Standards Committee subjects such documents to the same review as a full standard, with the understanding of all parties that the document is not a standard.

The current document is a committee report containing the text of a draft proposed standard, together with discussion materials and documentation used to draft the proposal. The material was drafted by the AESSC Working Group on Sound Reinforcement Components, under the chairmanship of Clifford A. Henricksen, as an addition to the published standard AES2-1984, "AES Recommended Practice — Specification of Loudspeaker Components used in Professional Audio and Sound Reinforcement." However, the Working Group members felt that while data obtained using the proposed method were not sufficiently repeatable and reproducible to have the full status of a standard, a standard could not be completed without further use of the proposed method in the field.

The writing group that prepared this document had the following members: Marshall Buck, Bernie Cahill, Robert T. Davis, Mark Gander, William Gelow, William Hayes, Clifford A. Henricksen (Chair), D. B. Keele, David Klepper (Secretary), Fancher M. Murray, George Owen, Daniel Queen, and Dilip Singhi.

At the time the document was edited for publication, the Working Group on Sound Reinforcement Components had the following members: Marshall Buck, John Bullock, Mahlon Burkhard, Kenton Forsythe, Mark Gander, Jim Long (Chair), David Martin, Richard Negus, Daniel Queen, Bob Thurmond and Jeff White.

At the time of approval of the document for publication, the AES Standards Committee had the following membership: Yoshi-Haru Abe, James S. Brawley, Richard C. Cabot, Peter D'Antonio, Donald Eger (Chair), Robert Finger, Irving Joel, William Hogan, Tomlinson F. Holman, Mike Klasco, David L. Klepper, Bart N. Locanthi, J. P. Nunn, Daniel Queen (Secretary), Tom Roseberry, W. T. Shelton, William D. Storm, Ted Telesky, Han Tendeloo, and Floyd E. Toole.

AES Information Document —
Plane-Wave Tubes: Design and Practice

1 General Comments

1.1 Purpose

The purpose of this document is to establish, expand, and improve the practice for the design and use of plane-wave tube measurement techniques, as recommended in section 2.2.1 of AES2-1984, "Recommended Practice Specification of Loudspeaker Components Used in Professional Audio and Sound Reinforcement."

1.2 Definition

A plane-wave tube is a device which is intended to provide a constant acoustical impedance with a value $\rho_0 c$ times the area of the inner diameter of the tube, where $\rho_0 c$ is the specific impedance of air. Measurement of the standing-wave ratio (SWR) of the tube determines the consistency of this "ρc termination" (see 2.3.2). Plane-wave tubes are used to provide a standard, frequency-invariant load for the testing of compression drivers, so that all drivers may be evaluated on an equal basis.

2 Design Practice

2.1 Usable Bandwidth

2.1.1 High-Frequency Limit. The high-frequency limit of a plane-wave tube is $1.22c/d$ where c is the speed of sound in air and d is the tube diameter. The measured response at the frequency determined by $1.22c/d$ is characterized by a narrow, deep notch. Above this frequency, a series of harmonically related notches will occur, so data taken in this region are considered unreliable.

2.1.2 Low-frequency Limit. Measurements at frequencies greater than $c/4l$, where l is the tube length, will provide reliable data.

2.1.3 Passband Acceptability. A SWR of less than 2 dB is acceptable for obtaining accurate data between the high- and low-frequency limits, as described in 2.1.1 and 2.1.2.

2.2 Tube Construction

2.2.1 Tube Materials. Plane-wave tubes may be constructed from a variety of materials. Clear plastic, such as acrylic or polycarbonate, is particularly useful when it provides a view of the acoustical absorbing material which has to be fixed to the interior of the tube.

2.2.2 Tube Assembly

2.2.2.1 The tube should be packed with acoustical absorbing material that provides enough absorption to make the SWR constant within 2 dB over the working range of the tube. A usual configuration is a tapered wedge of absorbing material — equal in length to that of the tube — which varies linearly from zero thickness at the tube entrance to the full width of the tube at the tube exit.[1] Blocking the end of the tube should have no effect on the performance if the absorbing wedge is made correctly.

2.2.2.2 The driver may be affixed to the tube by a variety of methods, the two most common being (1) direct flange mount to the exit hole and (2) a direct flange mount with a tapered insert which fits into the usual expanding throat

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[1] Common materials are 3 lb/ft^3 (48 kg/m^3) fiberglass, and 70 to 90 pore-per-inch Scott reticulated foam (available from Scott Paper Foam Division, Essington, PA).

of the driver. The second method allows a smaller tube diameter (which may be more suitable for frequency-response measurements) to be used while not changing any driver loading parameters. However, the first is preferred, since it gives to-the-horn performance information, in particular with regard to distortion. In either case, the plane-wave tube or any added connecting air channel from the driver to the tube should not be smaller in area than the total area at the entrance to the driver's phasing plug immediately adjacent to the diaphragm. Otherwise the net compression ratio (diaphragm-to-phasing-plug area ratio) of the driver will increase from its design value, so erroneous performance (response and distortion measurements) will be observed. For example, most 4-in (100-mm) diaphragm, 2-in (50-mm) exit compression drivers have a 10:1 compression ratio. Therefore a 1.25- or 1.26-in (31.75- or 32-mm) diameter plane-wave tube would be the smallest usable without changing the loading characteristics of the driver.

2.3 Definitions

2.3.1 Sensitivity. For sensitivity and efficiency measurements, one acoustic watt is equal to 153 dB sound-pressure level in a 1-in (25.4-mm) reference diameter standard tube, or 160 dB for 0.16-in^2 (0.0001-m^2) area. The sensitivity varies as the inverse square of the tube diameter, or 20 log of the ratio of the diameter to the reference diameter.

2.3.2 Standing-Wave-Ratio Calibration. Standing waves may be expected if the tube absorbing material does not totally absorb the sound wave. If there is too much absorbing material, a wave will reflect from the impedance mismatch due to the stuffing, and if there is not enough, the wave will partially pass through and reflect from the open end of the tube.

The SWR in decibels indicates the sound-level variation along the length of the tube. The ratio should be measured at various frequencies. It may be expressed as the range of sound-pressure-level variation along the length of the tube. To measure it, select a longer than desired tube with the absorbing wedge inserted into the desired usable length of the tube at one end. At the other end, seal a small-cone loudspeaker with a hole drilled through both the cone and the magnet. The hole should be large enough for an open *probe tube* (a tube of negligible diameter compared to a wavelength of sound being measured), which has a microphone connected to its outer end and which is free to slide in and out. The pickup point will then be the open end of the probe tube, which is inserted into the measurement area. The microphone/tube probe then samples sound-pressure levels at various frequencies, over at least a four-wavelength range, to determine the SWR.[2] A SWR of 0 dB indicates that full absorption, hence no reflection, is taking place, so only plane waves progress down the tube, where they are fully absorbed in the wedge material.

A convenient indication of the SWR is the pattern of impedance variation about the theoretically straight-line impedance response of a driver mounted on the tube at low frequencies. If the ripple damps out at higher frequencies before the band of interest is reached, then the SWR will also be acceptable at these frequencies.

2.4 Measurement Practice: Microphone Placement and Use

2.4.1 Longitudinal Placement

The measurement microphone should be as close to the driver connection opening as possible.

2.4.2 Radial Placement.

The measurement microphone diaphragm should be placed radially in the wall of the plane-wave tube so that it is in the position of a chord of the inner diameter of the tube, equal in length to half the microphone diaphragm diameter. See Fig. 1.

2.4.3 Angular Placement

The measurement should not be affected significantly by angular placement anomalies, such as those caused by

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[2] The Bruel & Kjaer catalog has a description of an equivalent apparatus, model 4002, which is used in the same manner.

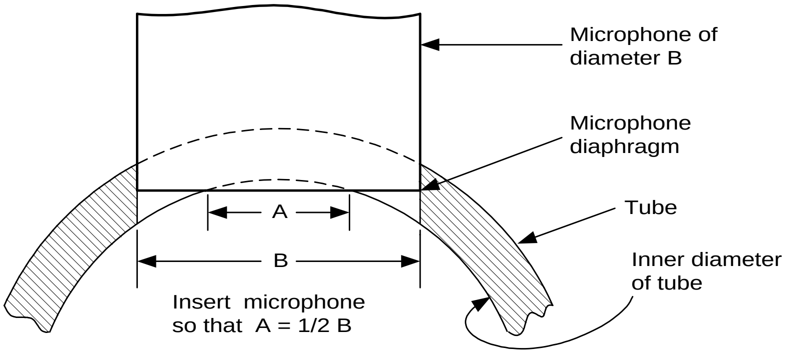


Fig. 1. Cross section of recommended tube/microphone interface (proportions exaggerated for clarity).

helical high-frequency modes set up by certain driver configurations. To assure this, several measurements should be made at various angles.

2.4.4 Microphone Attachment

The microphone should be air sealed to its probe hole. This can be accomplished by a tight fit, a flexible adhesive, grease, or an O-ring seal.

2.4.5 Microphone Type

The microphone should be a pressure-type precision microphone per American National Standards Institute (ANSI) S1.12-1967. A free-field type may be used in a plane-wave tube over a more restricted frequency range, as shown in manufacturers' catalogs. 1/4-in microphones are ideal for this application, since they can tolerate very high sound-pressure levels, and their size versus the wavelengths of sound being measured makes them easy to install without causing response problems.

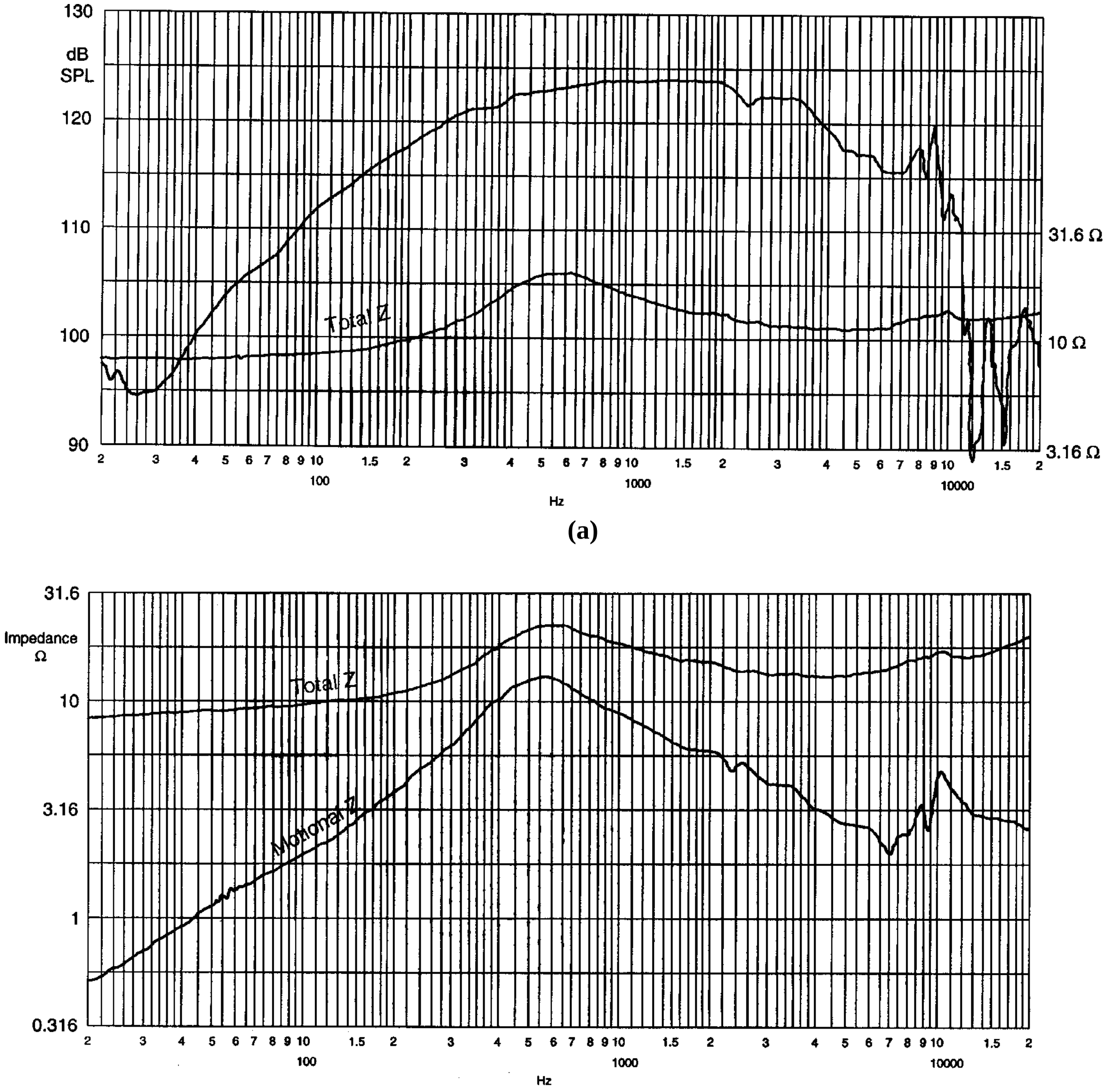
Appendix

The following comments are presented as guidance in the use of the "AES Recommended Practice — Specification of Loudspeaker Components used in Professional Audio and Sound Reinforcement."

In regard to 2.2.2.2, Fancher Murray submitted the curves given in Figs. A1 and A2, showing the same 2-in (51-mm) throat driver on both a 2-in (51-mm) and 1-in (25-mm) plane-wave tube. Note that the same driver on the 1-in (25-mm) tube has better high-frequency response, *especially in the region of 7 kHz or so*, due to the change of net compression ratio or phase plug loading caused by the small tube.

In regard to 2.4.1, *the committee felt that the measurement at the throat of a driver being measured would provide the most useful data because it would apply to any horn to which the driver was mated.*

Marshall Buck supplied some relative data on an alternative method: measuring "at least 10 wavelengths of the highest frequency" down the tube, which is an old rule of thumb used by electoacousticians. However, the committee agreed that this method introduced much more cumulative air distortion than the measurement at the throat.



(a)

(b)

Fig. A1. 2485 narrow surround driver, 2-in (51-mm) diameter throat, on 2-in (51-mm) diameter tube.

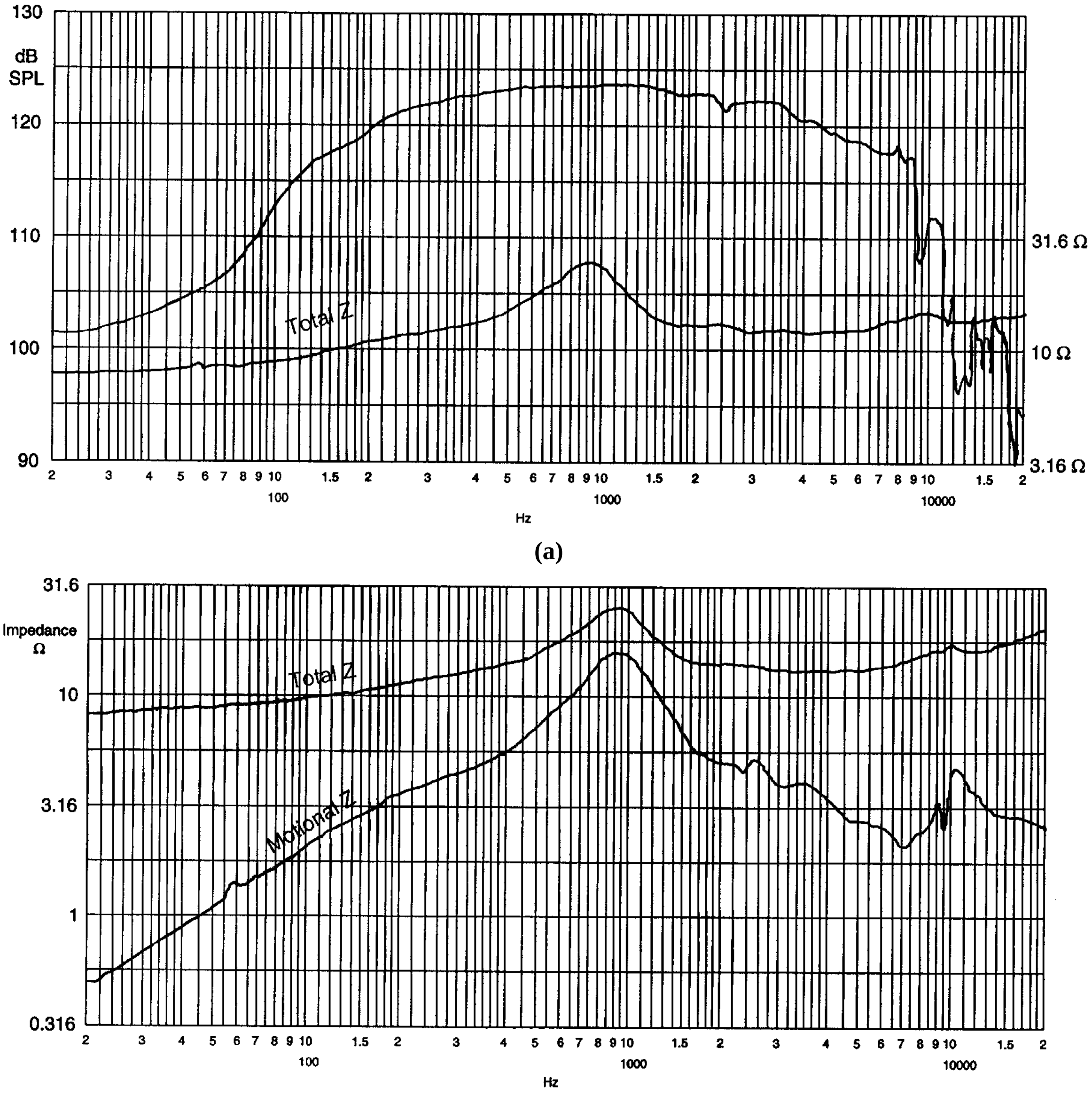
In regard to 2.4.2, the trick is to make the microphone diaphragm behave as if it were the wall of the tube.

Obviously, this is easier to accomplish with a small microphone, and this is the reason that most laboratories use a 1/4-in microphone for plane-wave tube work.

Fancher Murray sent more data on some studies of radially placed microphones, including the effect of the protective grid, and tube termination. His comments follow (edited):

"I am enclosing several copies of the charts [Figs. A1 – A3]. This work relates to construction of curved 2-in (51-mm) plane-wave tubes for use on the production line (for quality assurance) that would closely simulate the straight engineering plane-wave tube.

"The engineering tube is straight and is of 2-in (51-mm) diameter. Since the JBL transducers are really 1.9-in (48-mm) there is a 2-in (51-mm) tapered section formed of molded epoxy to make a smooth transition between the transducer and the 2-in (51-mm) tube. The tube is standard transparent 2-in (51-mm) water pipe of polyvinyl chloride plastic.



(a)

(b)

Fig. A2. 2485 narrow surround driver, 2-in (51-mm) diameter throat, on 1-in (25-mm) diameter tube.

"The termination is 6.56 ft (2 m) long and is made of reticulated polyurethane foam having 80 pores per inch. It is tapered throughout its length and is treated to be age and fire resistant.

"The microphone connection admits a Bruel & Kjaer 1/4-in microphone without grid so that the diaphragm is held tangent to the inside surface of the 2-in (51-mm) tube. It may be noted that a 1/4-in (6-mm) flat in a 2-in (51-mm) tube departs from the curvature of the tube by 0.002 in (0.05 mm) so that there is an insignificant difference between being tangent and being full secant. The microphone is mounted through the flange of the tube (also a standard pipe fitting) so that it is approximately 1/2 in (12.7 mm) from the end of the tube.

"The quality-assurance tube is constructed in a similar manner, except that the tube is straight for 26 in (0.66 m). At this point it connects to a standard long-radius pipe elbow to make a 90° turn and then continues on for another 26 in (0.66 m). The elbow has a 12-in (305-mm) radius of curvature with a circumferential length of about 19 in (0.48 m), so that the total tube length is approximately 71 in (1.8 m).

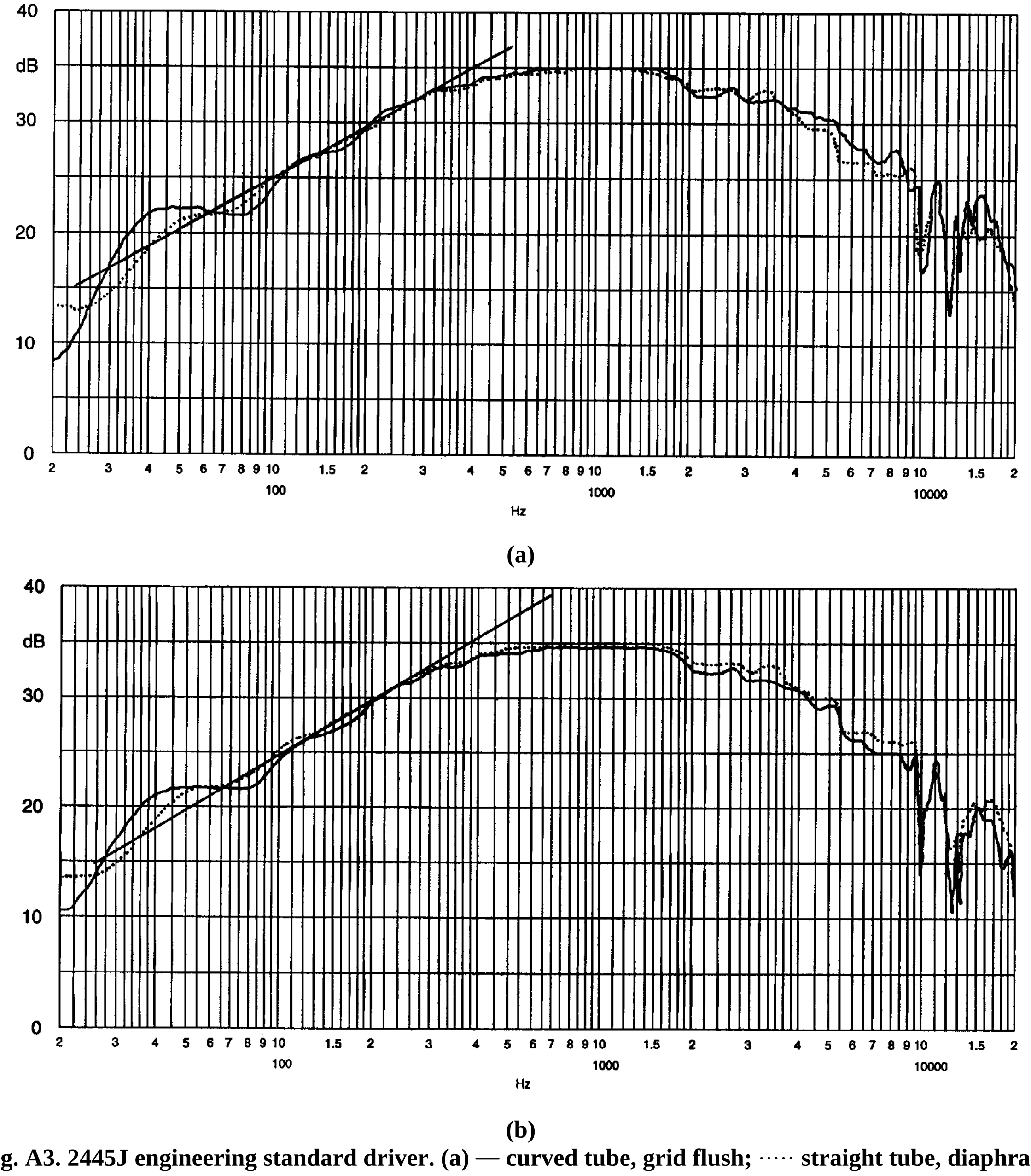


Fig. A3. 2445J engineering standard driver. (a) — curved tube, grid flush; ····· straight tube, diaphragm flush, without grid. (b) — curved tube, diaphragm flush, with grid; ····· straight tube, diaphragm flush, without grid.

"This tube has a termination of the same material as the engineering tube, but the paper is only 47 in (1.2 m) long, the rest of the tube being filled solid with polyurethane foam.

"The curves show three regions of difference between the two tubes: (1) low frequencies between 20 and 400 Hz;

(2) midrange from 3000 to 10 000 Hz; and (3) above 12 000 Hz.

"In region 1, the effects of the shorter taper length of the quality-assurance tube are clearly seen as differences in the standing waves. If it may be assumed that the transducer itself is cutting off smoothly (a reasonable assumption), then the deviations from a smooth curve may be taken as being the result of the reflections from the termination. A 6.56-ft (2-m) termination is a quarter-wavelength long at 43 Hz and should absorb 99 % of incident energy at that frequency. This produces a SWR of 1.5 dB. The dotted curve [Figs. A3(a) and (b)] appears to deviate approximately 1 dB from a straight line [drawn through the points (20, 13) and (400, 35) on the charts] at 45 Hz, so the ideal is reasonably approached.

"The shorter termination would be expected to show a similar deviation at 71 Hz, where it is a quarter-wavelength long. Indeed this appears to be the case. Thus it is reasonable to use a fine-pore reticulated foam having a taper length of a quarter wavelength at the lowest frequency of interest.

"In region 2, the differences between the solid and dotted curves [Figs. A3(a) and (b)] appear to be differences in the construction of the tapers. Parts (a) and (b) of Fig. A3 represent conditions wherein there are two independent tapers in the tube [Fig. A3(a)] and wherein the two tapers have been glued together to form a single unit [Fig. A3(b)]. These differences may be considered important depending on the nature of the task to be performed.

"Region 3 is of the greatest interest for purposes of this letter. Other charts have shown that the differences at 15 kHz are not due to the physical differences discussed above. These differences are entirely due to microphone placement.

"Fig. A3(a) shows microphone response when its grid is tangent (visually) to the surface of the tube, while Fig. A3(b) details the response when the microphone diaphragm is tangent to the tube surface. The two dotted curves, being generated in the straight tube, always show the response when the diaphragm is tangent and the grid is not present.

"Experiments in the quality-assurance tube indicate that it does not matter whether or not the grid is present when the diaphragm is tangent to the inside surface of the tube.

"The notches shown in the responses at 10, 12.5, and 13 kHz cannot, at this time, be attributed to wave effects in the tube. It is known that the 10 kHz notch is the result of diaphragm resonance, and I currently assume that the others are too.

"In summary, it may be stated that the taper length of the termination is the important parameter at the low-frequency end; that something goes wrong in the midrange if the termination presents two different points to the sound wave; and that the microphone diaphragm should be tangent to the inner surface of the tube for best high-frequency response. The grid of a 1/4-in microphone does not appear to affect frequency response below 20 kHz.

"The use of a tube smaller than the transducer output throat cannot be justified without clear indications of this in the report. The acoustic impedance presented to the diaphragm has been shown to be inversely proportional to the tube area and is automatically incorrect if the tube is small."