serted in the metallic section to measure drivers of different throat areas. All the measurements reported here were performed with two 25.4-mm (1-in) exit drivers (Altec Lansing 909-8A and RCF N450) and the MLSSA™ measurement system.

1.2 Inverting the Wedge

The main implementation issue we had to deal with was the arrangement of the absorbing material. We used a soft polyester fiber with a density of 10 kg/m^3. Using a soft material, it is rather difficult to cut a long wedge with smooth, regular tapering. Even more, the wedge would not stand in the correct position without a rigid skeleton or some kind of supporting structure. So we looked for an alternative solution.

We cut a series of disks having the same diameter as the inner section of the tube out of the absorbing material. In those disks we cut out concentric circles of increasing areas, thus obtaining rings of different thicknesses. Then we put full disks in the far end of the tube and rings of diminishing thicknesses proceeding toward the driver and microphone. This way we set up a sort of inverted wedge [Fig. 1(b)], thinking that such a structure could gradually absorb the outgoing waves as well as the structure proposed by AES.

2 EXPERIMENTAL VERIFICATION

2.1 Standing-Wave Ratio Test

In an infinite lossless tube there would be a progressive wave only, traveling unchanged in its original direction. That is what should happen in a perfect plane-wave tube too. In this theoretical case, a signal of equal amplitude could be measured at every point.

To evaluate any deviation from ideal behavior in a real plane-wave tube, the AES document suggests measuring the "standing-wave ratio," that is, the amount of amplitude variations along a tract of the tube. This kind of measurement is the same used in the "Kundt tube" to test absorbing materials. It requires an assembly of a driver with a hole in the membrane and a magnet as well as a small microphone probe to slip through the hole. In the case of the plane-wave tube, there would not be room enough to move the probe between the driver and the beginning of the absorbing wedge, so the AES document suggests the use of another tube, with the same cross section, to test the effectiveness of the absorption.

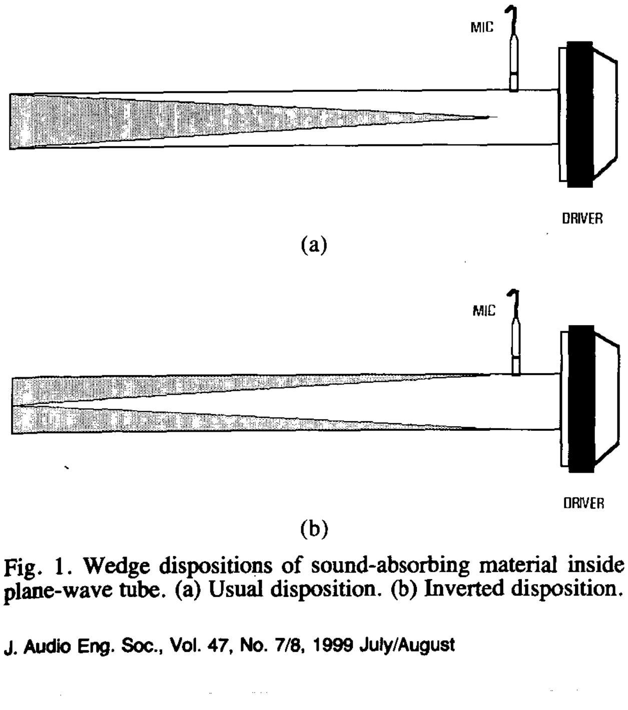

Fig. 1. Wedge dispositions of sound-absorbing material inside plane-wave tube. (a) Usual disposition. (b) Inverted disposition.

2.2 Open versus Closed End

In our case it would have been very difficult to move all the absorbing rings to another tube and back to the first without altering the disposition. Therefore the test results would have been unreliable. Then we devised another test, which can be performed without moving the absorbing material. What the standing-wave ratio test seeks to settle is the amount of residual reflections from the far end of the tube. Those reflections are the effect of the acoustic impedance mismatch at the physical termination of the device. According to the AES document [3], "blocking the end of the tube should have no effect on the performance if the absorbing wedge is made correctly." So the first part of the test was a comparison between two measurements performed under the same conditions, changing the far-end termination from open to closed. The results, illustrated in Fig. 2, show a good behavior, with differences within 1.6 dB, down to 60 Hz. The low-frequency limit of the tube is set at $c/4l$, where l is the physical length of the tube. The effective length of the tube, including the metallic section and the fitting, is 1.42 m. Calculating with a speed of sound $c = 344$ m/s, the result is 60.6 Hz, in agreement with the experimental results.

2.3 Empty versus Filled Tube

But this test is not sufficient to ensure the correct operation of the tube. Again from the AES document [3], "if there is too much absorbing material, a wave will reflect from the impedance mismatch due to the stuffing." This effect is independent of the far-end condition, and so cannot be detected by the test described previously. In that case our comparison term was an empty tube.

When using a measurement system based on maximum-length sequences (MLS), one can perform measurements of the impulse response in a reflecting environment—such as an empty, open tube—and then retain only the time segment preceding the first reflection, the so-called anechoic section (Fig. 3). In this part of the impulse response there is no difference between a tube of finite length and an infinite one. A comparison between the empty-tube frequency response and that of the plane-wave tube is shown in Fig. 4. The difference between the curves is within 0.7 dB up to 8 kHz. About 8 kHz we find a definite notch, and from this point on the differences are larger (2–3 dB and more). But this is not due to an impedance mismatch affecting high frequencies only. From just about 8 kHz another band-limiting mechanism comes into play—the transverse modes of vibration of a cylinder of air.