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STANDARDS

AES Information Document for Acoustics - Plane-Wave Tubes - Design and Practice

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AES Information Document for Acoustics - Plane-Wave Tubes - Design and Practice

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Abstract

The standard AES2 calls for the use of plane-wave tube measurement of high-frequency 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.

2013-02-11 printing

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Foreword

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

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.

Foreword to second revision, 2012

This 2012 edition is a revision of AES 1id-1991 (r2003)

Additional uses of a plane-wave tube are listed. Further tests were performed to compare a distant microphone location with a close location to test the hypothesis that non-plane-wave radiation would be more accurately measured. A termination method is described. A modern method of calibration is referenced and summarized.

Dimensions have been converted into SI units throughout, but the original US conventional units have also been retained for reference.

Note on normative language

In AES standards documents, sentences containing the word “shall” are requirements for compliance with the document. Sentences containing the verb “should” are strong suggestions (recommendations). Sentences giving permission use the verb “may”. Sentences expressing a possibility use the verb “can”.

AES Information Document for Acoustics - Plane-Wave Tubes - Design and Practice

1 Introduction

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 AES2, "Recommended Practice - Specification of Loudspeaker Components Used in Professional Audio and Sound Reinforcement." [C.1]

1.2 Definition

A plane-wave tube (PWT) is a device which is intended to provide a constant acoustical impedance with a value $\rho_0 c$ divided by the area defined by 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 "$\rho_0 c$ 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. In addition, when properly terminated, it is anechoic.

Uses of plane wave tubes for compression driver testing include:

1 Frequency response measurements
2 Distortion measurements
3 Coherence measurements
4 Power testing
5 Power compression testing
6 Listening tests

The use of a PWT does not replace testing a driver on a horn in an anechoic environment; it is an adjunct to it.

2 General

2.1 Usable bandwidth

2.1.1 High-frequency limit

The high-frequency limit, in kHz, of a plane-wave tube is 0,586*c*/*d* where *c* is the speed of sound in air, in m/s, and *d* is the tube diameter in mm. The measured response at the frequency determined by 0,586*c*/*d* is characterized by a narrow, deep notch. Above this frequency, a series of Bessel-function-related notches will occur, so some data taken in this region may be considered unreliable. The following table 1 shows the first six modes:

Table 1 - Resonant modes

PWT cross-modes	*c*=344 m/s	Mode Frequency, kHz					
	Mode No, type	1 Assym	2 Assym	3 Symm	4 Assym	5 Assym	6 Mixed
Inside Diameter mm (in)	25,4 (1)	7.936	13.17	16.52	18.11	22.93	22.98
	38,1 (1,5)	5.291	8.780	11.01	12.07	15.29	15.32
	50,8 (2)	3.968	6.585	8.260	9.055	11.47	11.49

2.1.2 Low-frequency limit

Measurements at frequencies greater than $c/4l$, where l is the tube length in metres, 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. The tube must have a rigid wall. Thin wall acrylic tube exhibits spurious resonances, and if used, it should be covered with a layer of SoundKote or equivalent damping material. Beranek (6) recommends that a measurement tube be made of precision seamless steel with a wall thickness of 1/4 inch (6.35 mm), and if possible the tube should be buried in sand or coated with mastic to reduce mechanically borne waves.

For power testing, the material must be tough, so it won't easily crack. PVC water pipe is tough and well damped, although one should make sure the inside diameter is sufficiently close to the desired size.

2.2.2 Tube assembly

2.2.2.1 Acoustical absorbing material

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] The absorbing wedge in the PWT may be constructed with a large number of varying lengths of long-haired wool yarn. The number of strings must be sufficient to fill the tube tightly at its distant end. Pairs of strings may be cut at 25-mm intervals to provide a graduated absorbing wedge. Blocking the end of the tube should have no effect on the performance if the absorbing wedge is made correctly.

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

2.2.2.2 Driver mounting

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 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 compression drivers with a diaphragm diameter of 100 mm (4 in), and an exit diameter of 50 mm (2 in) have a 10:1 compression ratio. Therefore a plane-wave tube of diameter 31,75 mm or 32 mm (1,25 in or 1,26 in) would be the smallest usable without changing the loading characteristics of the driver.

2.3 Sensitivity

For sensitivity and efficiency measurements, one acoustic watt is equivalent to a sound-pressure level of 153 dB in a 25,4-mm (1-in) reference diameter standard tube, or 160 dB for an area of 0,16 in^2 (0.0001-m^2). The sensitivity varies as the inverse square of the tube diameter, or 20log of the ratio of the diameter to the reference diameter.

2.4 Standing-wave-ratio calibration

2.4.1 Standing-wave-ratio

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 standing-wave ratio (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. 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.

2.4.2 Calibration using modern equipment

Tests of the adequacy of the PWT can be made using gated time domain MLS or equivalent measurements. First, the empty (unterminated) tube (three feet long in this example) is measured, for a reference. The reference response is taken from the first 6 ms of the time domain response, before the reflections from the open end of the three-foot tube have a chance to interfere with the direct sound. Thus the reference is anechoic. An FFT using a Blackman-Harris half window works well to get the reference frequency response. Then the stuffed, terminated tube is measured using a long time record, such as 200 ms. The comparison is from an FFT of the full 200 ms of response. The error function of the PWT is then the ratio of the gated anechoic frequency response measurement and the long time frequency response measurement.

A typical error function is shown below in figure 1.

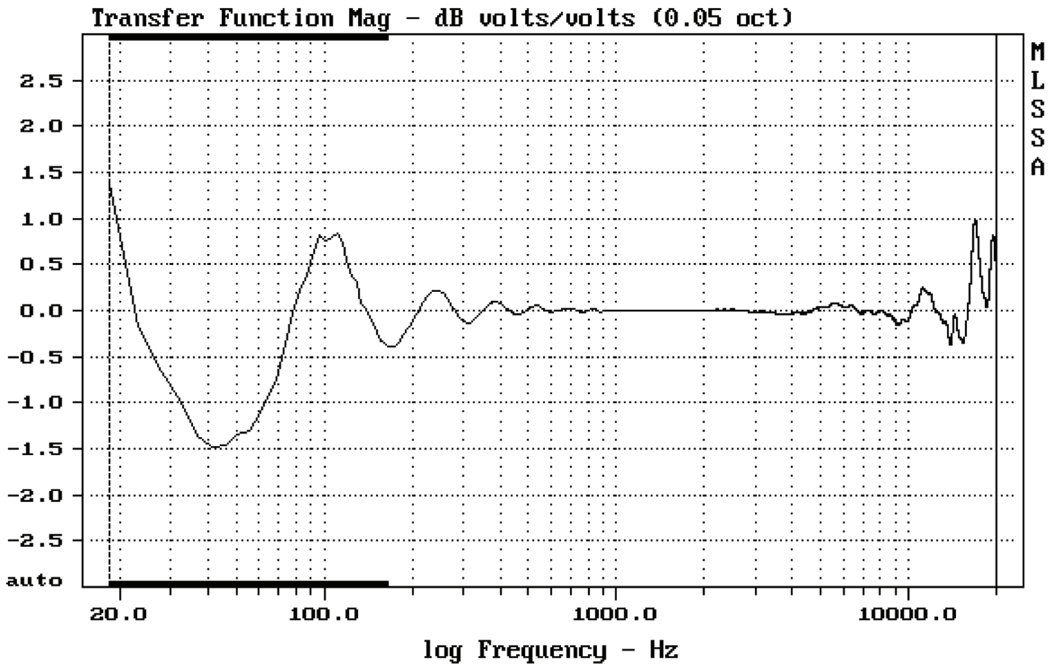


Figure 1 - Typical error function

The error above 65 Hz is less than 1 dB, between 500 Hz and 8 kHz less than 0,1 dB, while the error at very low frequencies is 1,5 dB at points. There is a 1 dB error at about 15 kHz, The anechoic region with less than 1 dB error of this PWT is thus 65 Hz to 20 kHz.

This technique is also described in reference [C.2].

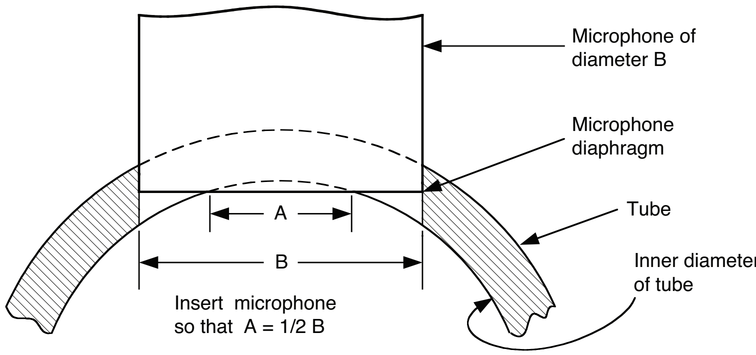
2.5 Measurement practice: Microphone placement and use

2.5.1 Longitudinal placement

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

2.5.2 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 figure 2.



NOTE - proportions exaggerated for clarity

Figure 2 - Cross section of recommended tube/microphone interface

2.5.3 Angular placement

The measurement should not be affected significantly by angular placement anomalies, such as those caused by helical high-frequency modes set up by certain driver configurations. To assure this, several measurements should be made at various angles.

2.5.4 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.

2.5.5 Microphone type

The microphone should be a pressure-type precision microphone [C.7]. 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.

2.6 Velocity distribution at the horn throat

“For the numerical simulation (BEM) of horns, the sound velocity distribution at the horn throat is required as one boundary condition. It is common to use plane wave excitation even at high frequencies since the shape of the real wave front in general is unknown. The error in the simulation result (directivity / frequency response) is difficult to predict and can only be judged by measurement of the real system. To achieve accurate simulation results the specific velocity distribution of each driver is required which must be measured at the interface between horn driver and horn. A more general approach for simulation techniques is created using modal composition. Measurements and simulations of different systems are compared to verify this method”. From [C.5]

Annex A: Discussion

The following comments are presented as guidance in the use of AES2, "AES Recommended Practice - Specification of Loudspeaker Components used in Professional Audio and Sound Reinforcement."

A.1 Tube assembly

In regard to 2.2.2.2, Fancher Murray submitted the curves given in Figures A.1 and A.2, showing the same 51-mm (2-in) throat driver on both a 51-mm and 25-mm (1-in) plane-wave tube. Note that the same driver on the 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.

A.2 Longitudinal microphone position

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 electro-acousticians. However, the committee agreed that this method introduced much more cumulative air distortion than the measurement at the throat. See Annex B.

A.3 Radial Placement

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 6,35 mm (1/4-in) microphone for plane-wave tube work.

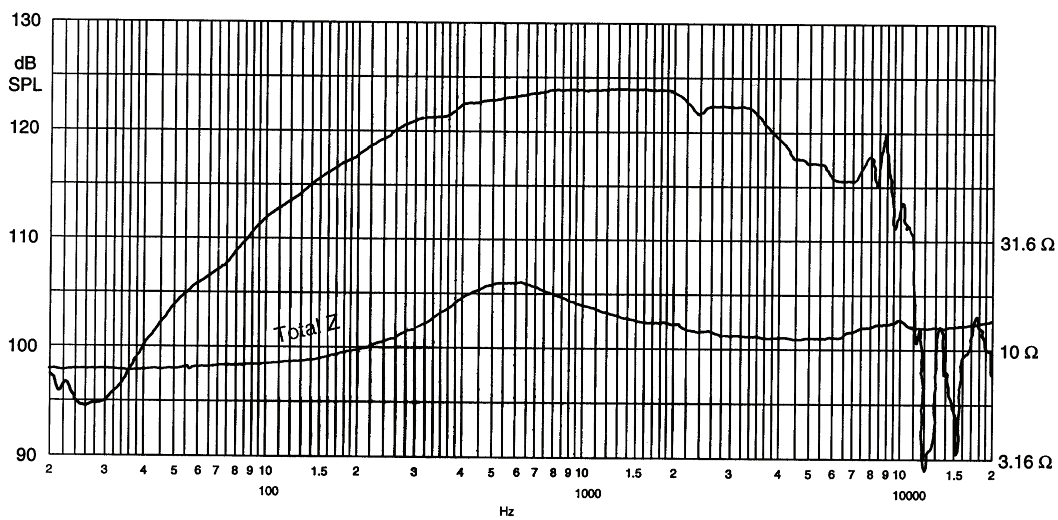


Figure A.1a - JBL 2485 narrow surround driver, 2-in diameter throat on 2-in diameter tube

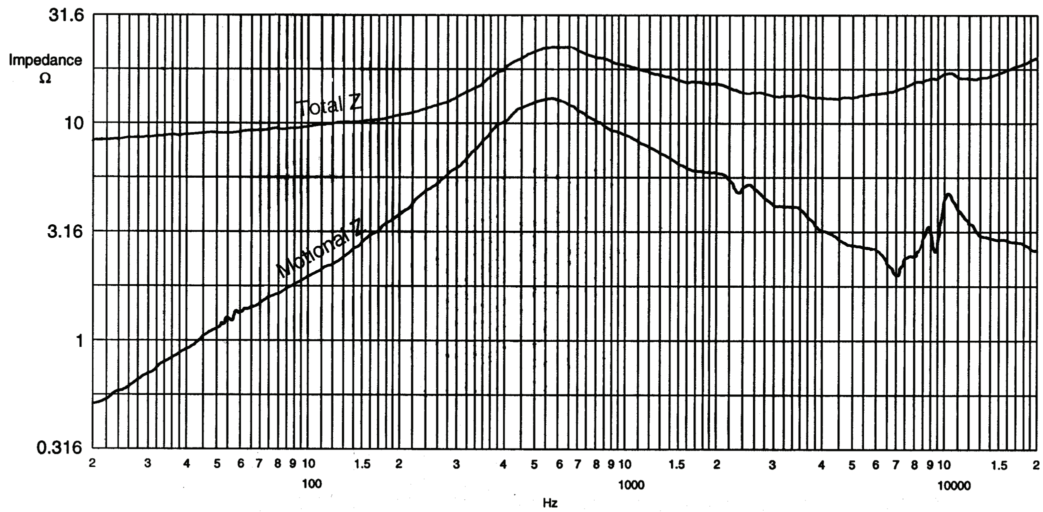


Figure A.1b - JBL 2485 narrow surround driver - 2-in diameter throat on 2-in diameter tube

A.4 Comments of F. Murray

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):

“This work relates to construction of curved 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 51-mm (2-in) diameter. Since the JBL 2485 transducers are really 48-mm (1,9-in) there is a 51-mm tapered section formed of molded epoxy to make a smooth transition between the transducer and the 51-mm tube. The tube is standard transparent 2-in 51-mm water pipe of polyvinyl chloride (PVC) plastic.

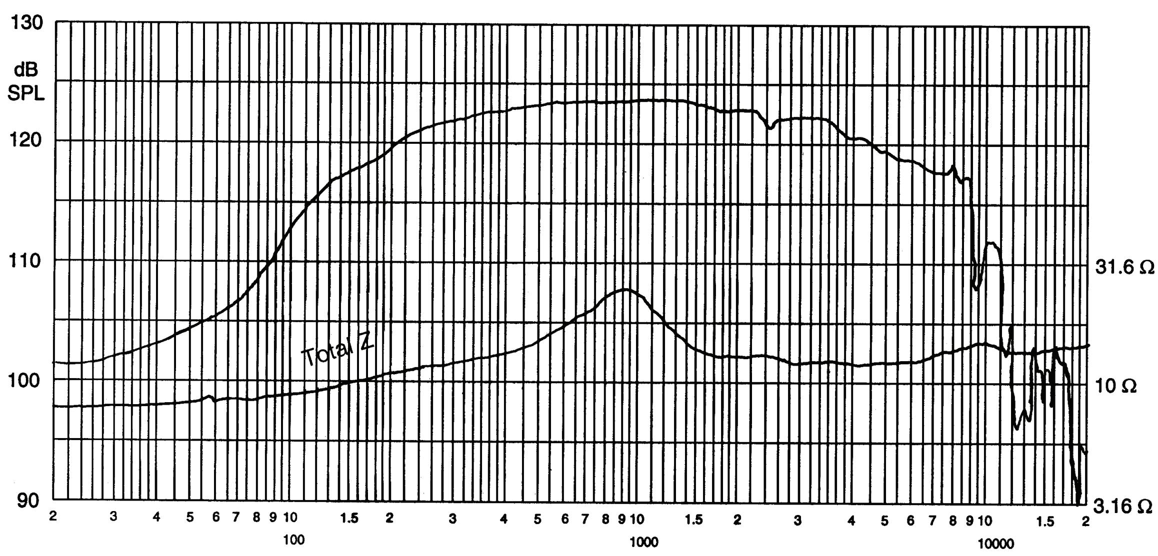


Figure A.2a - JBL 2485 narrow surround driver - 2-in diameter throat on 1-in diameter tube

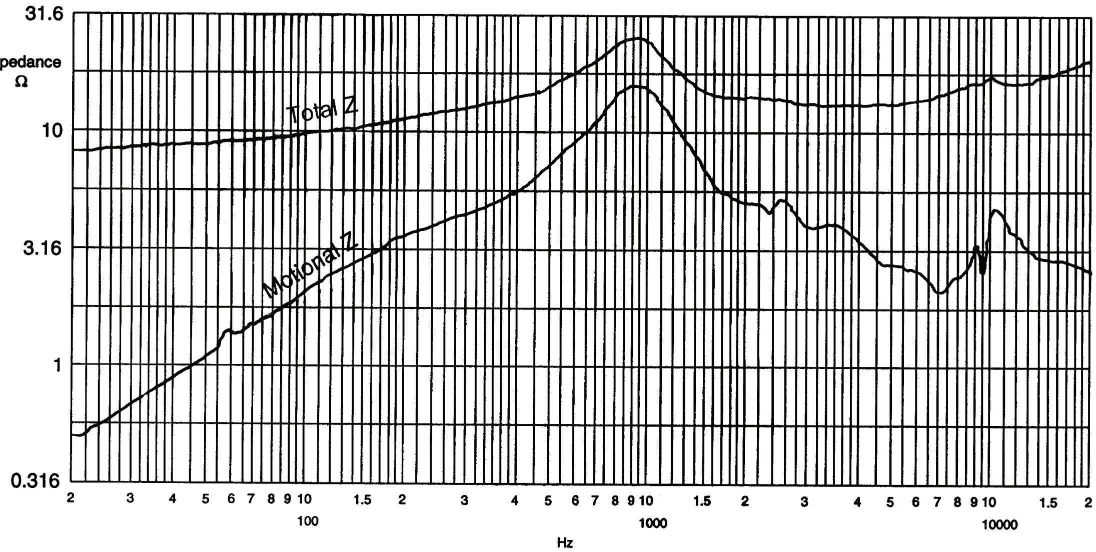


Figure A.2b - JBL 2485 narrow surround driver - 2-in diameter throat on 1-in diameter tube

“The termination is 2 m (6,56 ft) 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 51-mm tube. It may be noted that a 6-mm (1/4-in) flat in a 51-mm tube departs from the curvature of the tube by 0,05 mm (0,002 in) 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 12,7 mm (1/2 in) from the end of the tube.

“The quality-assurance tube is constructed in a similar manner, except that the tube is straight for 0,66 m (26 in). At this point it connects to a standard long-radius pipe elbow to make a 90º turn and then continues on for another 0,66 m (26 in). The elbow has a 305-mm (12-in) radius of curvature with a circumferential length of about 0,48 m (19 in), so that the total tube length is approximately 1,8 m (71 in).

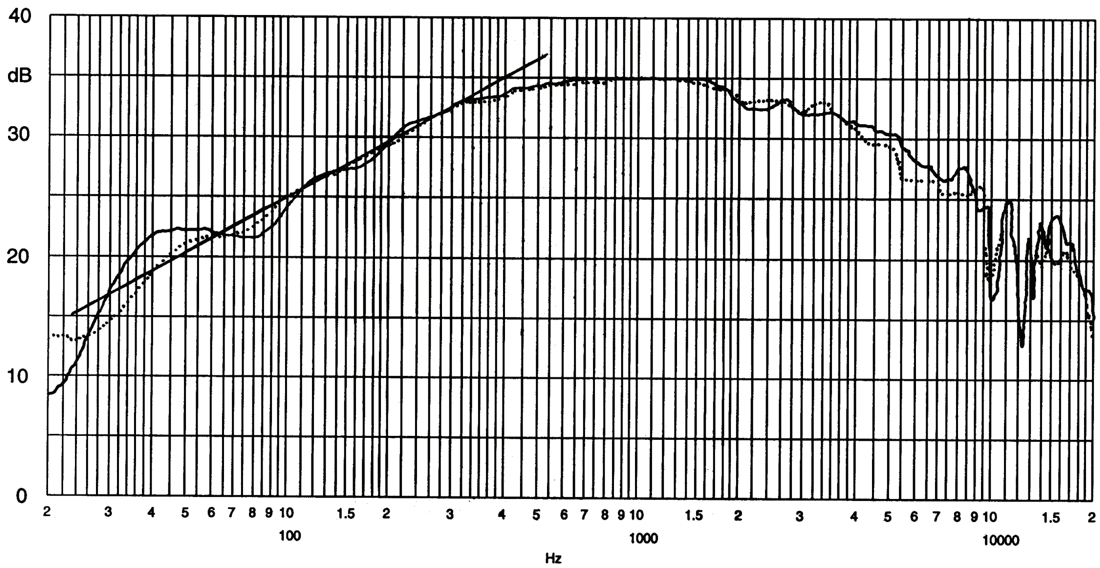


Figure A.3a - 2445J engineering standard driver

curved tube, grid flush;
••••• straight tube, diaphragm flush without grid

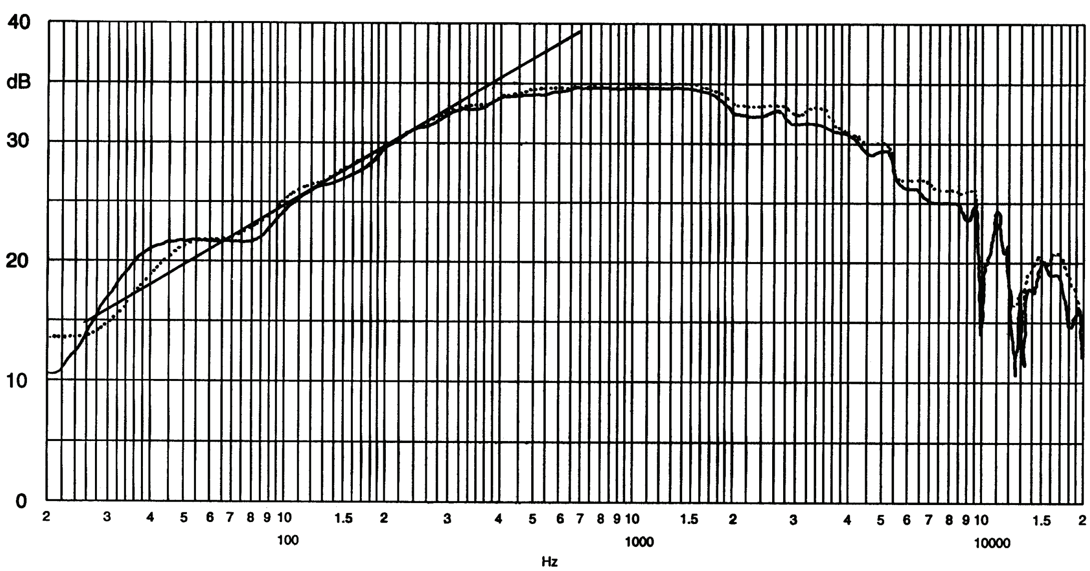


Figure A.3b - JBL 2445J engineering standard driver,

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 taper is only 1,2 m (47 in) 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 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 [figures A.3a and A.3b] 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 [figures A.3a and A.3b] appear to be differences in the construction of the tapers. Parts (a) and (b) of figure A3 represent conditions wherein there are two independent tapers in the tube [figure A.3a] and wherein the two tapers have been glued together to form a single unit [figure A.3b]. 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.

“Figure A.3a shows microphone response when its grid is tangent (visually) to the surface of the tube, while Figure A.3b 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.”

Annex B: Effects of microphone location on measurements of response and distortion

B.1 General

For these tests, a plane-wave tube was constructed with two microphone locations. The tube was mounted with the tube vertical and the driver at the top of the tube. The first microphone was located at 15,9 mm (0,625 in) from the driver mounting face, and the second 269,9 mm (10,625 in) lower in the tube. Two B&K 4135 1/4-inch microphones were used, with the protective grid in place.

The object was to compare measurements at the two locations.

B.2 Frequency

First, we look at the differences in frequency response, as measured with MLSSA. The driver was stimulated with 1 volt of MLS noise.

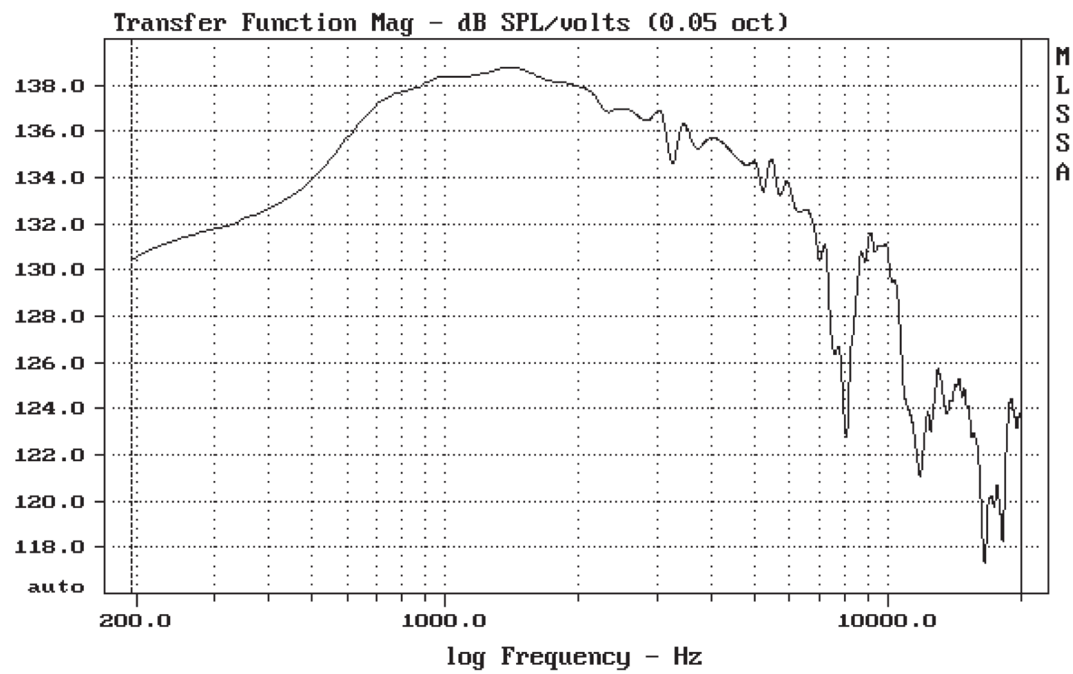


Figure B.1a - Upper microphone

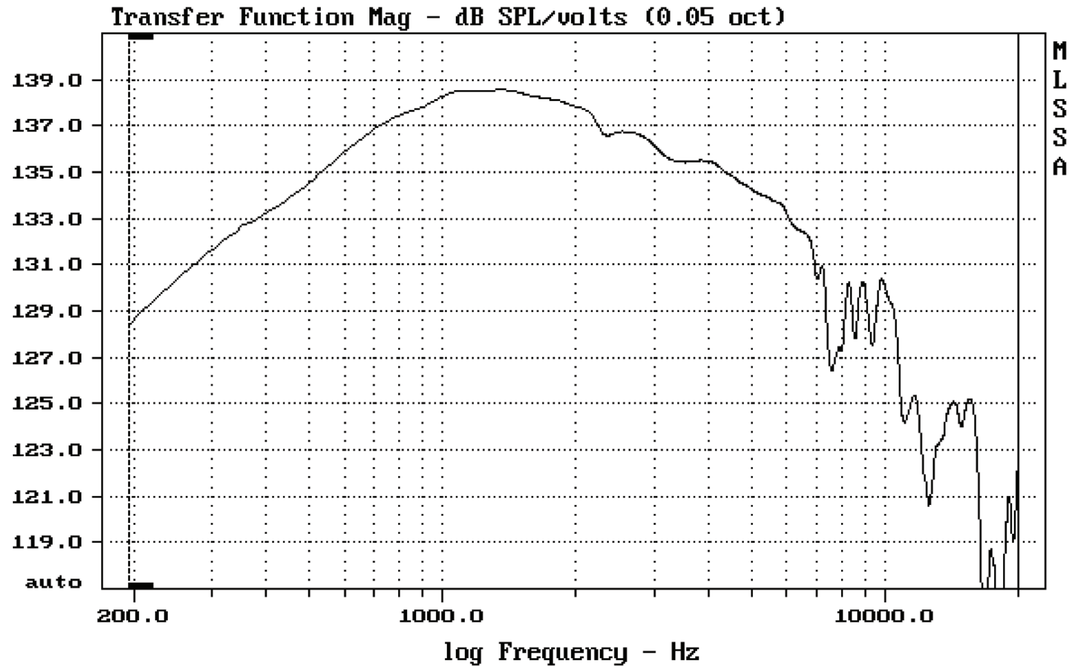


Figure B.1b - lower microphone

Note that the cross-mode dip at 8 kHz is much shallower in the lower microphone position.

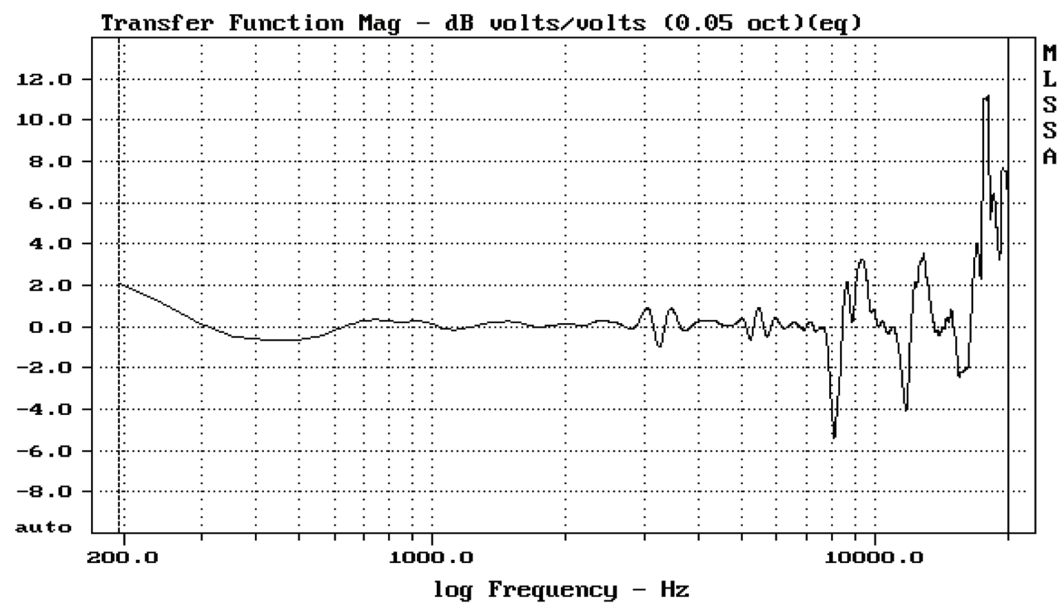


Figure B.1c - Difference (delta) between a & b

The ratio graph above shows that there is an increase in relative high frequency level at the lower microphone position.

Next, the driver was stimulated with an rms voltage of 18 V.

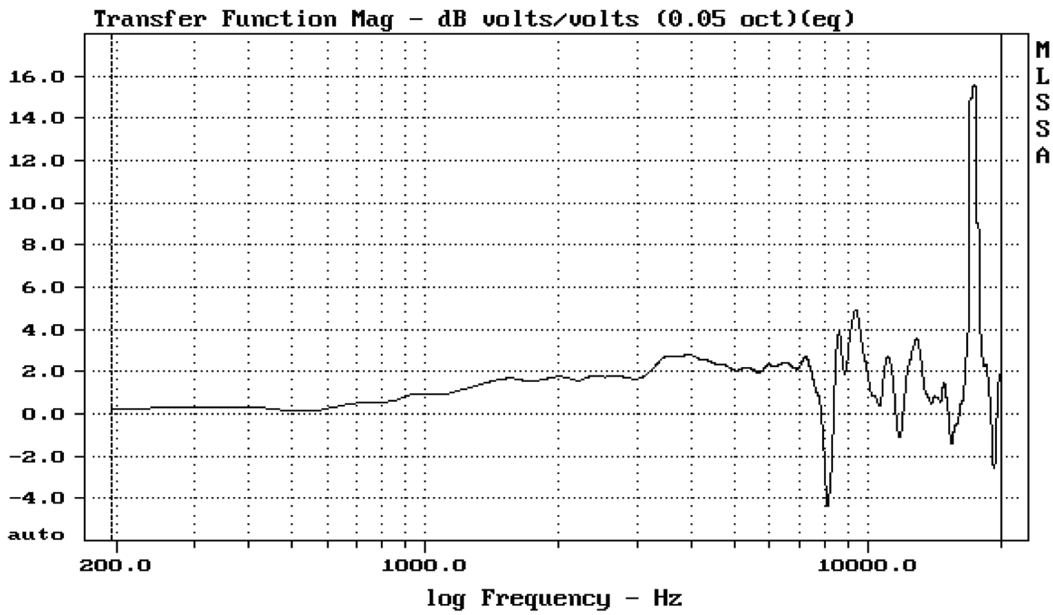


Figure B.1d - Difference between upper & lower microphones, 18 V drive

The relative increase in high frequency level is more pronounced with the 18 V drive, as sound pressure levels were in the region of 160 dB. A 2-dB increase is seen as low as 2 kHz.

B.3 Distortion

The following measurements, taken with a CLIO system, show the large increase in harmonic distortion that occurs at the lower microphone position. This distortion contributes to the increase in high frequency level.

First, see the response with a drive of 3 V. The distortion components are raised 20 dB. The colour red shows the fundamental, blue shows second harmonic, and green shows the third harmonic.

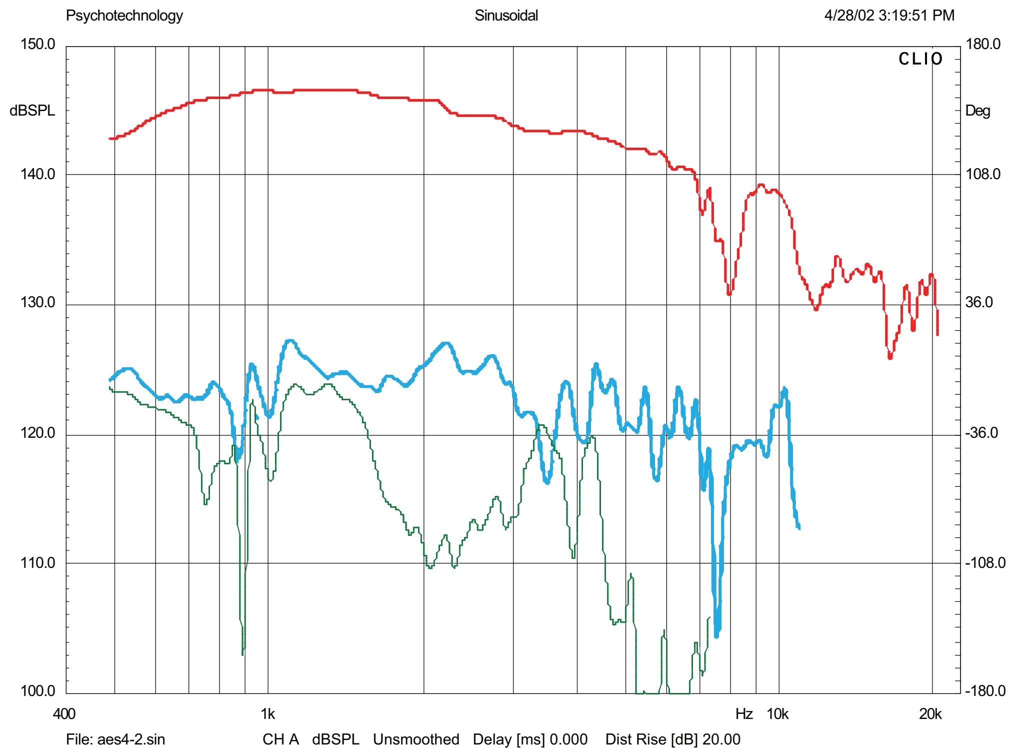


Figure B.2a - response from the upper microphone at 3 volts drive

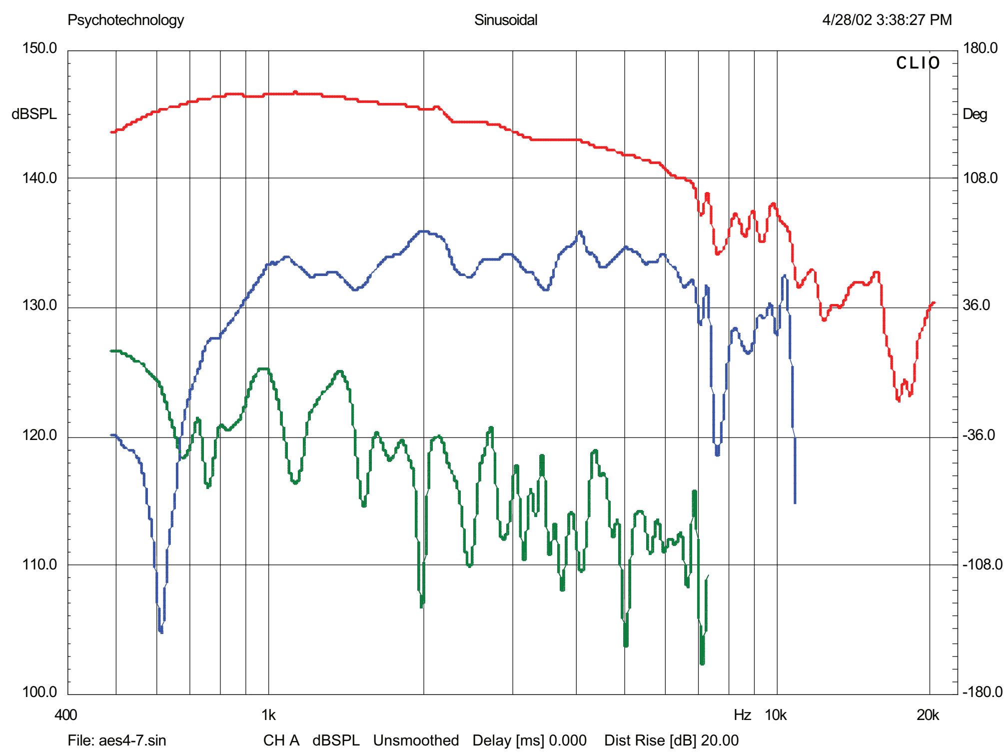


Figure B.2b - response from the lower microphone at 3 volts drive

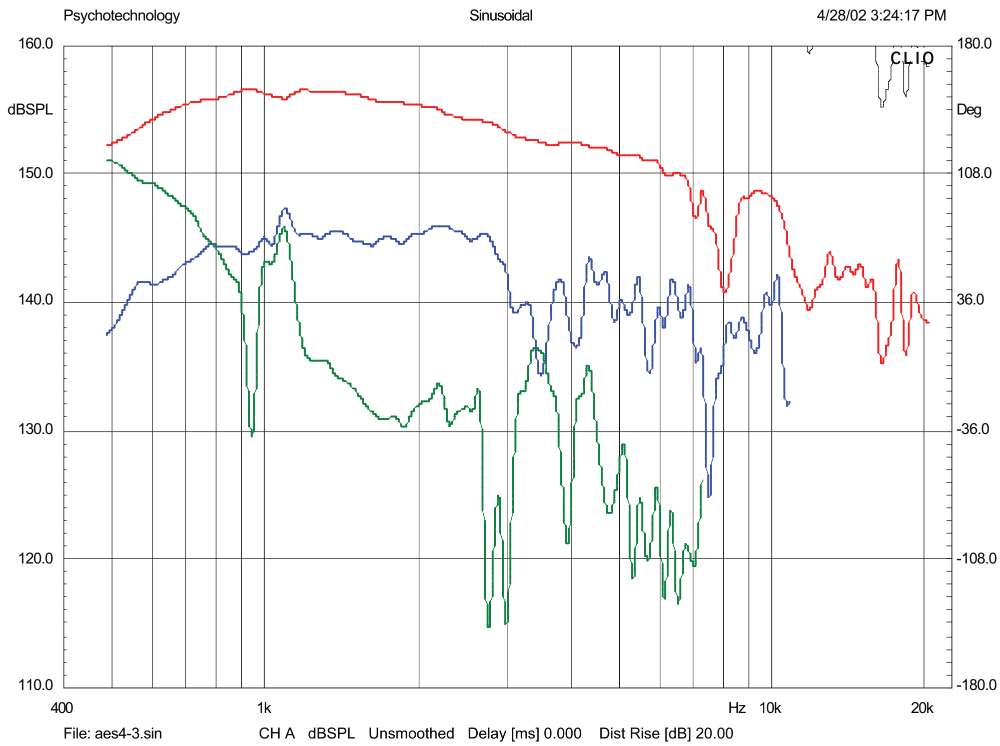


Figure B.3a - response from the upper microphone, 10 volts drive

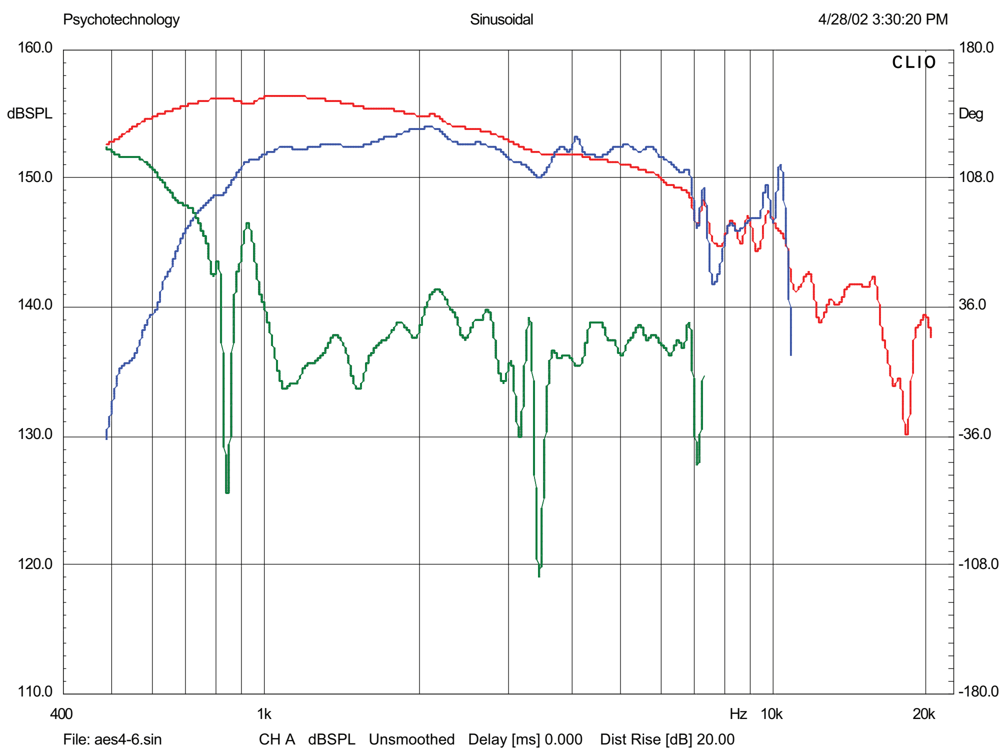


Figure B.3b - response from the lower microphone, 10 volts drive

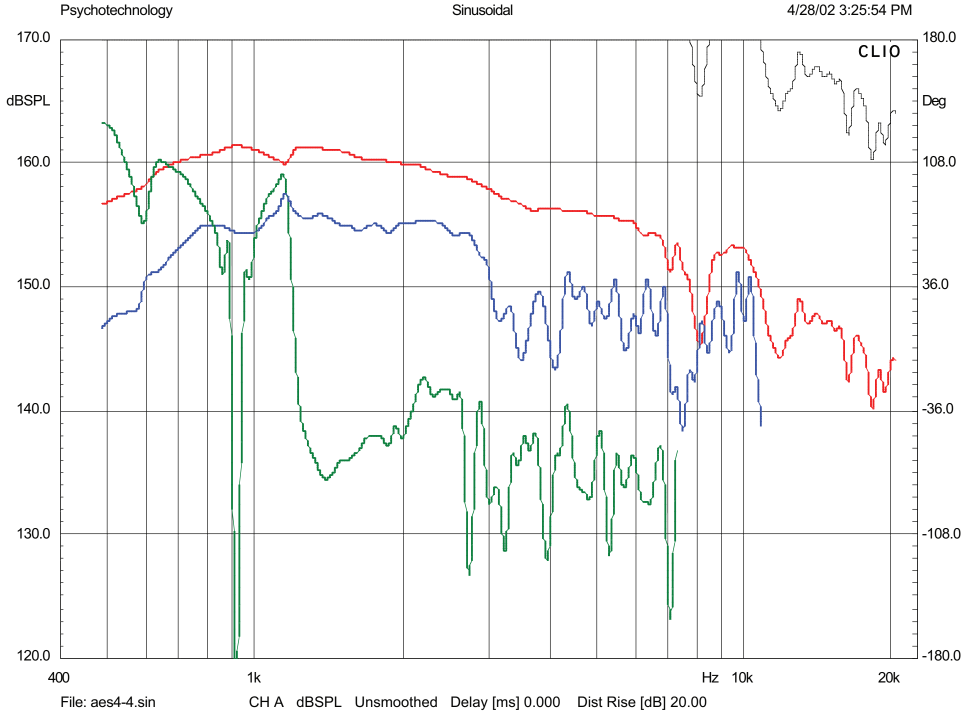


Figure B.4a - response from the upper microphone, 18 volts drive

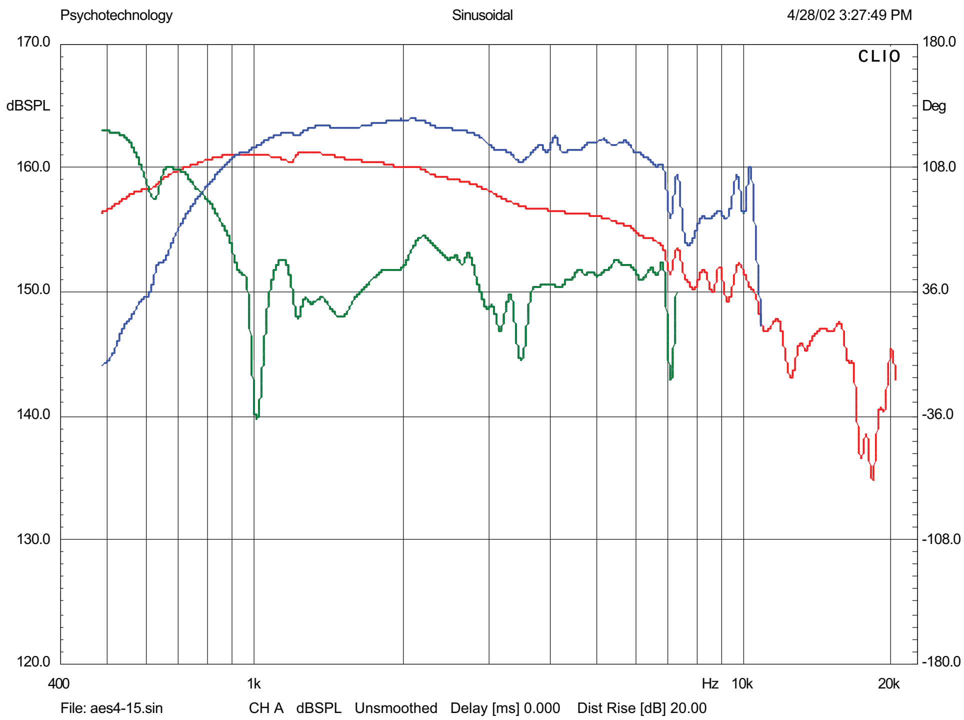


Figure B.4b - response from the lower microphone, 18 volts drive

Note that, in each case, the distortion rises 10 dB to 15 dB at the lower microphone position.

B.4 Plane wave errors

B.4.1 General

One issue encountered in testing drivers is that the waves are not always plane. This wave-front distortion may be caused by diaphragm asymmetries. When measuring with a close microphone position in a PWT, it may be necessary to rotate the driver through 3 or 4 positions and average the readings. The same issues may show up when measuring a driver on a horn; the far-field polar pattern may change with driver rotation.

There are two proposed additional solutions when using a PWT:

- Average the output of three microphones placed at the same distance from the driver at 120-degree rotations. This is not discussed further here.
- Place the microphone lower down (10 PWT diameters) in the PWT. This offers an opportunity for the higher order modes to damp out, as they do not propagate as efficiently. The down side is that there is more distortion, due to the longer distance traveled in the confines of the tube. This can increase the measured level of the high frequencies. This effect is more pronounced at higher output levels.

B.4.2 Ten-diameter microphone position

To test this proposal, a 1-in PWT with two microphone locations - 15,8 mm (5/8 in) from the opening, and 270 mm (10 5/8 in) from the opening - was used. For the following tests a JBL 2425J driver was used, driven at 1 volt with MLSSA. The following graphs show the difference in response from one rotation of the driver and one 180 degrees from it, at a given microphone location. It is clear that both microphone positions yield similar results; that is the lower position offers no improvement in eliminating variance from non-plane-wave excitation.

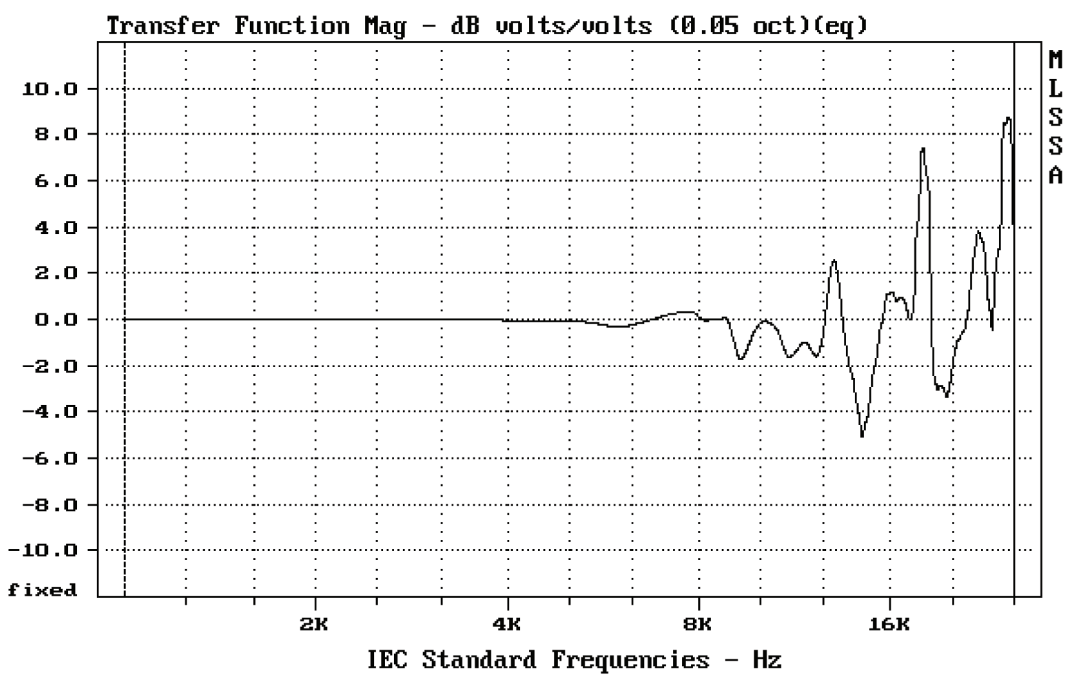


Figure B.5a - Upper microphone, delta with driver rotated position

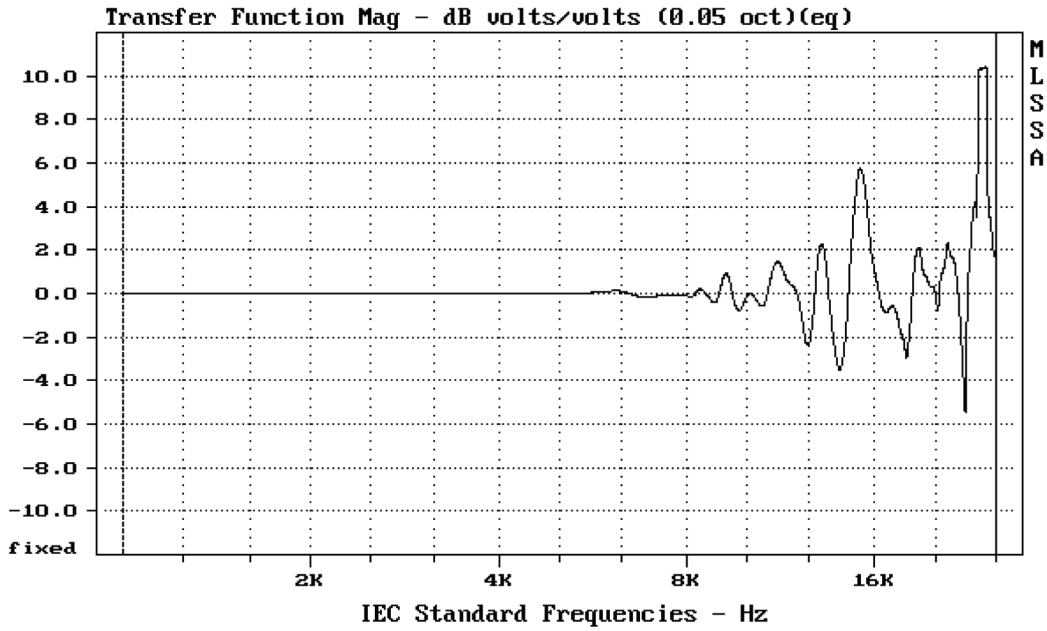


Figure B.5b - Lower microphone, delta with driver rotated position

B.4.3 PWT calibration at two microphone locations

To assure that the ragged behavior at high frequencies is due to non-plane-wave activity, the calibration procedure was performed for both microphone locations.

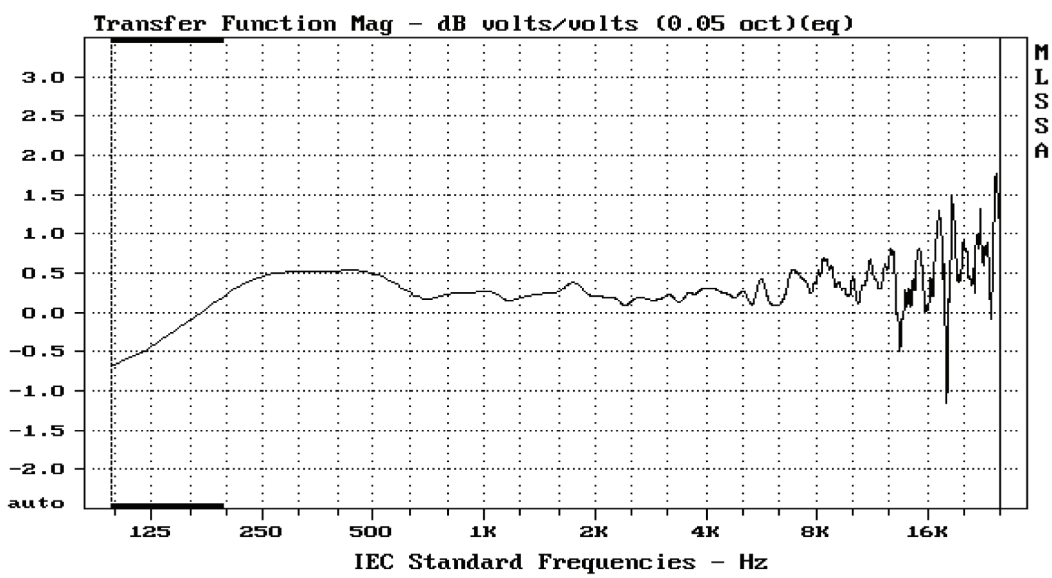


Figure B.6a - error for upper microphone

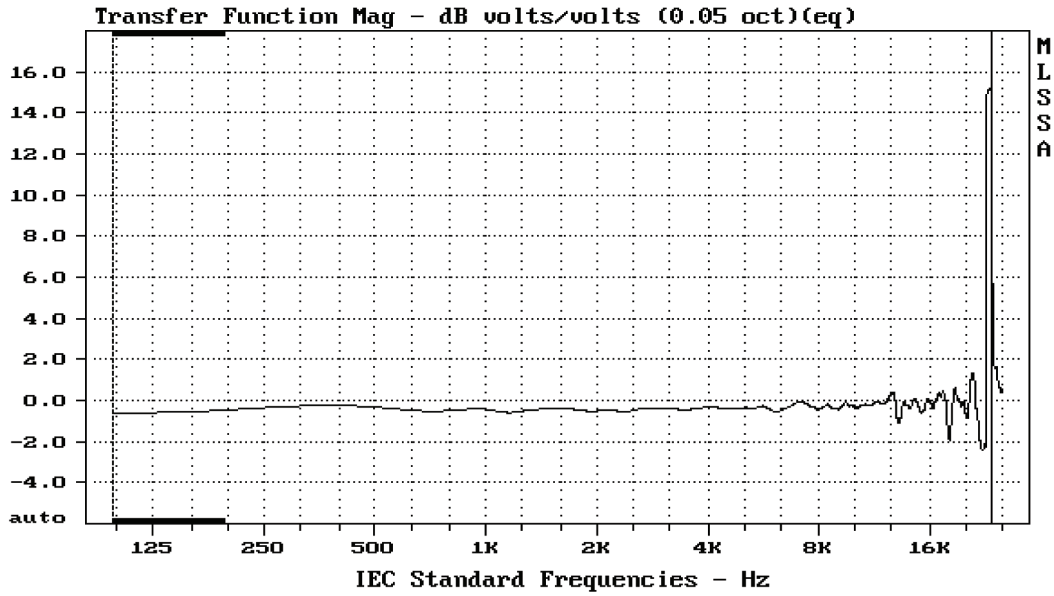
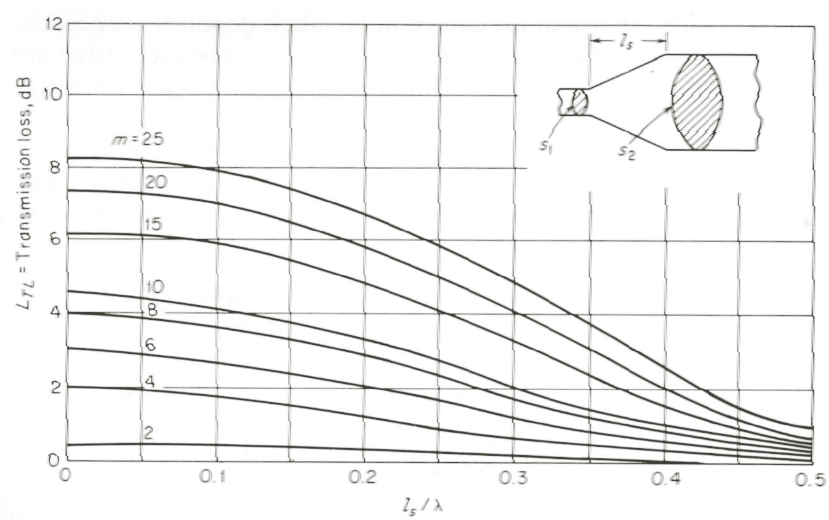


Figure B.6b - error for lower microphone

B.5 Acoustical considerations for use of conical connecting sections

The following graph from reference [C.4] provides attenuation figures for conical connectors. For modest area ratios of 10 or less an attenuation of less than 1 dB can be achieved at 1 kHz with a section length of 152 mm (6 in).



The transmission loss of conical connectors as a function of the non-dimensional parameters l_s/λ and $m = S_2/S_1$. As shown, l_s is the length of the conical section measured along the axis of the duct.

Figure B.7 - Transmission losses

It would be useful to experiment with a section that reduced the 51 mm (2-in) exit of a 102 mm (4-in) diaphragm driver with a diaphragm area of 81,3 mm^2 to 8,1 mm^2 (12,6 in^2 to 1,26 in^2), which would be approximately 32 mm (1,25 in) in diameter. This would raise the modal frequencies by a factor of 1,6 referenced to a 51 mm (2-in) tube. The distortion levels would be expected to rise, but frequency response measurements would be extended in accuracy.

B.6 Conclusions

For accurate distortion measurements, the microphone location should be close to the entrance to the tube.

No improvement in measurement of non-plane-wave behavior is accomplished with the distant microphone location.

Calibration of the PWT can be achieved by graphing the ratio of the time gated frequency response to the ungated terminated response.

A thorough understanding of the complexity of cross modes is necessary in order to separate driver response from PWT errors. See reference [C.5].

Annex C: Informative references

[C.1] **AES2-2012**, *AES standard for acoustics - Methods of measuring and specifying the performance of loudspeakers for professional applications - Part 1: Drive units*, Audio engineering Society, New York, NY., US.

[C.2] *Building a Plane-Wave Tube: Experimental and Theoretical Aspects*. Roberto Magalotti, Carlo Zuccatti, and Paolo Pasini. Journal of the Audio Engineering Society, Engineering Report, July/August 1999, Volume 47, Number 7/8.

[C.3] *Plane Wave Tubes – Uses and Limitations*. Marshall Buck, Convention Paper 6268, 117th , October 2004.

[C.4] *Noise and Vibration Control*. Leo Beranek, Editor. 1988 Institute of Noise Control Engineering. Chapter 12, Mufflers, T.F.W. Embleton, page 377.

[C.5] "*On the Velocity Distribution at the Interface of Horn Driver and Horn*" Preprint Number: - 6097 - Convention: 116 (May 2004) Authors: Behler, Gottfried K.; Makarski, Michael

[C.6] *Acoustical Measurements.* Leo Beranek. Revised Edition 1988, 1993. Acoustical Society of America. Chapter 7, *Measurements of Acoustic Impedance*. [Page 320 shows in addition the equation for the high frequency limit in Hz in a tube of diameter d in cm as 20,000/d. This is essentially the same as the Mode-1 calculation is 2.2.1 above.]

[C.7] **IEC 61094** *Measurement microphones*, International Electrotechnical Commission, Geneva, Switzerland. Published in several parts, currently:

IEC 61094-1 Ed.2:2000 *Measurement microphones – Part 1: Specifications for laboratory standard microphones*

IEC 61094-2 Ed.2:2009 *Electroacoustics - Measurement microphones - Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique*

IEC 61094-3 Ed.1:1995 *Measurement microphones - Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique*

IEC 61094-4 Ed.1:1995 *Measurement microphones - Part 4: Specifications for working standard microphones*

IEC 61094-5 Ed.1:2001 *Measurement microphones - Part 5: Methods for pressure calibration of working standard microphones by comparison*

IEC 61094-6 Ed.1:2004 *Measurement microphones - Part 6: Electrostatic actuators for determination of frequency*

IEC/TS 61094-7 Ed.1:2006 *Measurement microphones - Part 7: Values for the difference between free-field and pressure sensitivity levels of laboratory standard microphones*

IEC 61094-8 Ed.1:2012 *Measurement microphones - Part 8: Methods for determining the free-field sensitivity of working standard microphones by comparison*