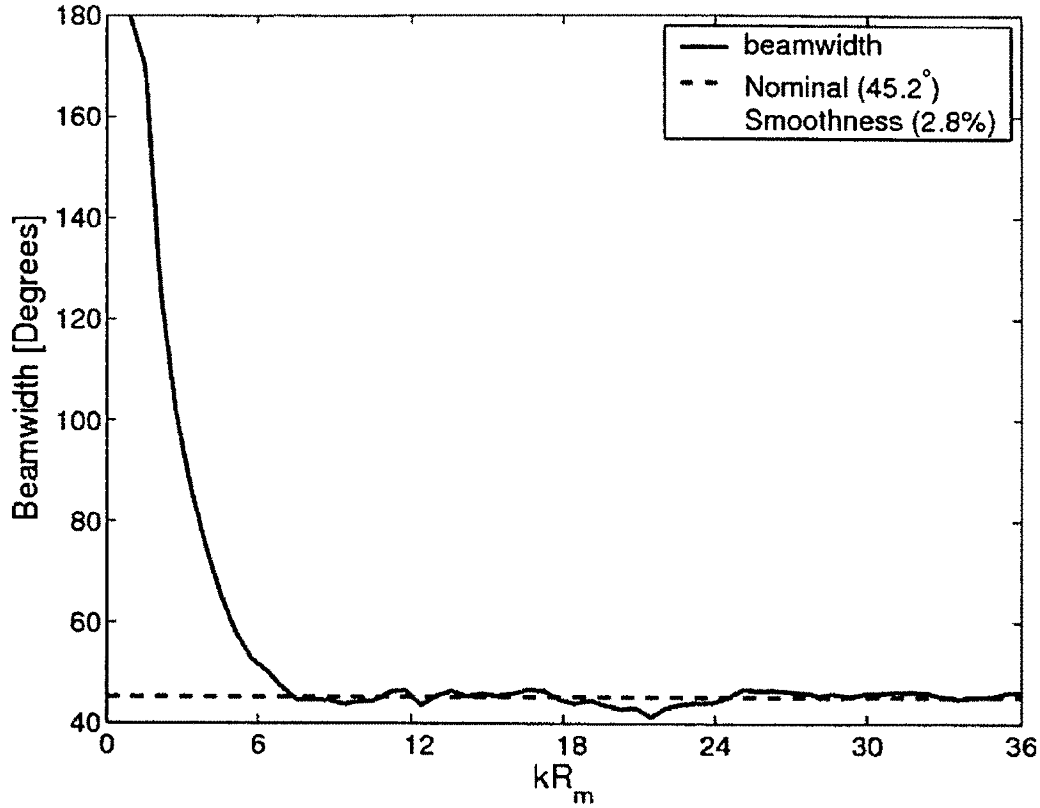
700



180
160
140
120
100
80
60
40
Beamwidth [Degrees]
0
6
12
18
24
30
36
kR m
beamwidth
Nominal (45.2°)
Smoothness (2.8%)

Figure 7

METHOD OF DESIGNING A SOUND WAVEGUIDE SURFACE

RELATED APPLICATIONS

The present application is a continuation of co-pending U.S. application Ser. No. 11/899,056, filed Sep. 4, 2007, which in turn, claims priority from Australian Provisional Patent Application Serial No. 2006904810, filed on Sep. 4, 2006. Applicants claim priority under U.S.C. §120 as to said U.S. application, and 35 U.S.C. §119 as to the said Australian application, and the entire disclosures of both of said applications is are incorporated herein by reference in their entireties.

TECHNICAL FIELD

The present invention relates to sound generation and reproduction. In a particular form the present invention relates to the design and specification of an acoustic horn or loudspeaker having improved spectral and spatial coverage characteristics.

INCORPORATION BY REFERENCE

The entire contents of each of the following document is hereby incorporated by reference:

R. C. Morgans, *Optimisation Techniques for Horn Loaded Loudspeakers*, PhD Thesis, University of Adelaide, 2004;

P. Kohnke, editor *ANSYS* 5.7 *Theory Manual*, Ansys Inc, Canonsburg, Pa., 8th edition, 2001

G. H. Koopman and J. B. Fahnline, *Designing Quiet Structures: A Sound Power Minimization Approach*, Academic Press, 1997; and

B. K. Beachkofski and R. V. Grandhi, *Improved Distributed Hypercube Sampling,* 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, 2002.

BACKGROUND

The aim of audio reproduction systems is to provide a high quality listening experience and clearly an important component of such a system is the sound delivery system which converts electrical signals to acoustic energy. Acoustic horns are well known sound delivery systems that function to increase sound output by appropriate loading of an electrically stimulated driver unit with the added ability to wholly or partly control the spatial distribution of sound generated by the driver. Typically, an acoustic horn utilises outwardly flaring walls to provide an expanding passage for the acoustic pressure wave between a throat entrance and a mouth exit. The acoustic horn is stimulated by the source driver unit located at the throat entrance which produces the acoustic pressure wave.

Whilst the wall profile of the acoustic horn may be axis-symmetric with an associated cross sectional area that is circular, in many cases the wall profile will have separate horizontal and vertical profiles and associated cross sectional areas which may be elliptical, or rectangular, or develop from one sectional area shape to another as one progresses from the throat to the mouth of the horn. This allows for the design of acoustic horns with well defined beamwidth that will suit a given environmental requirement. The beamwidth, also referred to as the angle of coverage, is defined as the angle formed between the −6 dB points of sound pressure level in the far field as calculated with respect to the central axis

reading. As an example, a given environmental requirement might include an acoustic horn having an angle of coverage of 90° in the horizontal plane by 40° in the vertical plane, or 60° by 40°, and so on. Generically acoustic horns of this nature are called constant directivity horns and may be used individually or incorporated into arrays to provide an extended angular coverage.

As such, two important features of an acoustic horn loudspeaker are the beamwidth, whether it be in one or two sectional planes, and the spectral content of the output pressure wave produced by the acoustic horn. Clearly, for asymmetric sound fields independent beamwidths can be determined for different planes of symmetry, in the process independently defining the width of the angle of coverage or the height of the angle coverage of the sound field produced by the acoustic horn. The beamwidth parameter of an acoustic horn also quantifies the amount of sound energy that is transmitted to off-axis regions where the central axis of a horn will be determined by the horn geometry.

With regards to the spectral content of the output pressure wave produced by the horn, this in principle should closely mimic the associated spectral content of the electrical input signal to the driver unit. Another important feature of an acoustic horn related to the beamwidth and spectral content of the output pressure wave is the variation of the beamwidth of the acoustic horn with frequency. Ideally, there should be no variation with frequency; otherwise the spectral content of the sound will vary depending on the location of a listener with respect to the central axis of the acoustic horn.

As is well known, the most important free parameter that may be varied when designing an acoustic horn is the shape of the horn as this shape forms a surface that directs the acoustic pressure wave. Accordingly, one prior art approach in attempting to obtain a sound field of uniform intensity over a desired beamwidth is to join two horn sections with differing cross sectional area growth rates together. The first section, typically employing an exponential area growth rate, provides low frequency loading to the driver and its profile is used to control the width of the sound energy in one plane. At the intersection of the differing area growth rates (called the diffraction slot), sound is diffracted and the intersection essentially becomes a secondary "line source" of sound. The second section, usually employing a conical area growth rate then provides beamwidth control in the second plane. Further flanges can then be added to obtain control over "mid frequency beaming" (a narrowing of the beamwidth at intermediate frequencies) and furthermore vanes can be mounted in the throat of the horn to attempt to obtain control over "high frequency beaming".

However, this approach has a number of serious disadvantages. Whilst a certain amount of control over the beamwidth can be achieved by use of a diffraction slot, this feature itself will also cause multiple reflections of sound waves within the horn, thereby resulting in an irregular frequency response which is easily measured and is perceived as colouration of the sound. Another significant disadvantage is that the sound emitted in the different planes will have different acoustic centres, these being defined by the respective centres of curvatures of the wavefronts of sound formed by the acoustic horn. Accordingly, acoustic horns based on the diffraction slot principle are difficult to incorporate into arrays where the alignment of individual horn components is an important consideration.

There have been a number of attempts to address the disadvantages of designs based on diffraction slots. One approach described in U.S. Pat. No. 6,059,069 relates to a loudspeaker horn having a straight wall section and a curved wall section. The straight wall section has diverging walls defining a coverage angle and the curved wall portion is connected to the straight wall portion at a point tangent thereto, and has a proximal end disposed perpendicular to the plane of the throat entrance. The diverging sidewalls define at least one coverage angle in orthogonal planes having a common apex in the plane of the throat entrance. Whilst this design is able to provide a common acoustic centre, thereby addressing one of the major disadvantages of diffraction slot designs, it only provides a relatively small amount of control of beamwidth in one axis as a function of frequency and this control is limited to only one axis.

US Patent Application No. 2003/0133584 employs an acoustic waveguide with a continuous least-energy-surface formed from an upper vertical control curve, a lower vertical control curve, right horizontal control curve and a left horizontal control curve. In addition, a circular throat end and a non-elliptical closed control curve form a mouth such that the continuous least-energy-surface is coincident with the six control curves. Again this design addresses the problem of providing a common acoustic centre but otherwise gives no guidance as to how a horn design having constant beamwidth as a function of frequency may be achieved.

In US Patent Application No. 2005/0008181, an acoustic waveguide is described that employs surfaces of constant coordinates in two coordinate systems. The coordinate systems chosen are those in which the equation that governs the propagation of sound either in the time domain (i.e. the wave equation,

$$\nabla^2 p(\vec{x}, t) - \frac{1}{c^2}\frac{\partial^2 p(\vec{x}, t)}{\partial t^2} = 0,$$

where $p(\vec{x}, t)$ is the acoustic pressure at position $\vec{x}$ and time t and c is the speed of sound) or alternatively in the equivalent frequency domain representation (i.e. the Helmholtz equation,

$$\nabla^2 p(\vec{x}) - \frac{\omega^2}{c^2} p(\vec{x}) = 0,$$

where $p(\vec{x})$ is the complex acoustic pressure at position $\vec{x}$ and ω is the circular frequency) are separable and accordingly yield simplified solutions that depend on single coordinates. For example in a cylindrical coordinate system, a surface of constant radius forms a tube and the propagation of sound down the length of the tube can be considered to depend on axial position only, at least at low frequencies. Another simple example is a spherical coordinate system consisting of the coordinates (r, θ, ϕ) where r is the radius, θ is the azimuth angle and ϕ is the zenith angle. A surface of constant ϕ gives a conical horn, and at low enough frequencies the propagation of sound can be considered to depend on r only. The use of a prolate spheroid coordinate system allows independent control of beamwidth but requires a cylindrical vibrating surface as an input. An elliptical cylindrical coordinate system then provides a match between a flat vibrating surface and the prolate spheroid waveguide.

Whilst in principle, horns shaped according to solutions of the Helmholtz equation should result in the beamwidth being independent of frequency the necessarily finite termination of the horn at its mouth will result in diffraction and reflection of the acoustic wave as it leaves the horn. This results in a severe degradation of the performance of the acoustic horn with respect to the constancy of beamwidth with frequency. As is noted in US Patent Application No. 2005/0008181, the outward terminating edge of the horn may be flared to attempt to reduce the variation of beamwidth with frequency. However, this empirical approach does not provide a reliable or systematic method for designing horns that have a desired beamwidth variation as a function of frequency.

It is the object of the present invention to provide a method capable of designing a sound waveguide surface having improved directional characteristics.

It is a further object of the present invention to provide a method capable of designing a sound waveguide surface having a beamwidth that varies with frequency in a predetermined manner.

SUMMARY

In a first aspect the present invention accordingly provides a method for designing a sound waveguide surface, the method including the steps of:

forming a parametric model of the sound waveguide surface, the parametric model having at least one input parameter;

simulating a sound field that is formed by the sound waveguide surface;

determining a frequency dependent spatial distribution measure for the sound field associated with the sound waveguide surface,

varying the at least one input parameter to change the sound waveguide surface to adjust the value of the frequency dependent spatial distribution measure.

In another form, the step of varying the at least one input parameter includes varying the at least one input parameter to adjust the frequency dependent spatial distribution measure towards a target criterion.

In another form, the step of varying the at least one input parameter includes determining an objective function characterising the difference between the frequency dependent spatial distribution measure and the target criterion.

In another form, the step of varying the at least one input parameter further includes minimising the objective function to generate a resultant value for the at least one input parameter thereby defining the sound waveguide surface having a frequency dependent spatial distribution measure approaching the target criterion.

In another form, the target criterion for the frequency dependent spatial distribution measure is based on the beamwidth variation of the sound field as a function of frequency.

In another form, the target criterion for the frequency dependent spatial distribution measure is a predetermined variation in the beamwidth as a function of frequency.

Alternatively, the target criterion for the frequency dependent spatial distribution measure is a substantially constant beamwidth as a function of frequency.

Alternatively, the target criterion for the frequency dependent spatial distribution measure is a predetermined constant beamwidth as a function of frequency.

In a second aspect the present invention accordingly provides a sound waveguide surface designed and constructed in accordance with the method of the first aspect of the invention.

In a third aspect the present invention accordingly provides a method for designing an acoustic horn, the method including:

forming a parametric model of the size and shape of the acoustic horn, the parametric model dependent on at least one input parameter;

simulating a sound field corresponding to the size and shape of the acoustic horn;

determining a beamwidth measure of the sound field, the beamwidth measure dependent on frequency and position; and

optimising the beamwidth measure with respect to a target criterion by varying the at least one input parameter.

In another form, the target criterion is a predetermined variation in the beamwidth as a function of frequency.

Alternatively, the target criterion is a substantially constant beamwidth as a function of frequency.

Alternatively, the target criterion is a predetermined constant beamwidth as a function of frequency.

In another form, the at least one input parameter includes a horn throat radius, a horn length, and a horn mouth radius.

In another form, the at least one input parameter furthers include a horn profile.

In another form, the horn profile is represented as a spline.

In another form, the acoustic horn is axially symmetric.

In a fourth aspect the present invention accordingly provides an acoustic horn designed and constructed in accordance with the method of the third aspect of the present invention

BRIEF DESCRIPTION OF THE DRAWINGS

Illustrative embodiments of the present invention will be discussed with reference to the accompanying drawings wherein:

FIG. **1** is a system flowchart depicting the method for designing a sound waveguide surface according to an illustrative embodiment of the present invention;

FIG. **2** is a side sectional view of an example waveguide surface geometry employed in an illustrative embodiment of the present invention;

FIG. **3** is a number of side section views of different horn profiles resulting from varying the input parameters of the waveguide surface geometry illustrated in FIG. **2**;

FIG. **4** is a contour map of the value of objective function S as a function of the horn dimension parameters R_m, R_t and L;

FIG. **5** is a contour map of horn shape parameter x_1 as a function of the horn dimension parameters R_m, R_t and L; and

FIG. **6** is a contour map of horn shape parameter x_2 as a function of the horn dimension parameters R_m, R_t and L.

FIG. **7** is a graph of the calculated beam angle versus frequency showing the high degree of smoothness obtained by using parameters selected from FIGS. **4**, **5**, and **6**.

DETAILED DESCRIPTION

The following description contains specific information pertaining to the implementation of the present invention. One skilled in the art will recognise that the present invention may be implemented in a manner different from that specifically discussed in the present application. Moreover, some of the specific details of the invention are not discussed in order not to obscure the invention. The specific details not described in the present application are within the knowledge of a person of ordinary skill in the art.

Referring now to FIG. **1**, there is shown a system flowchart of a method **100** for designing a sound waveguide surface according to an illustrative embodiment of the present invention. Throughout the specification the term sound waveguide surface is taken to mean a physical surface having properties capable of altering the directional characteristics of sound energy which interacts with the surface. The sound waveguide surface may also have further physical properties which enhance its absorptive or reflective capabilities as the case may be. Furthermore, the sound waveguide surface may also function in part as a sound emitter.

In overview, method **100** includes the steps of first inputting **110** a number of initial parameters into a parametric model **120** of the sound waveguide surface, the sound field for a parameterised sound waveguide surface is then simulated **130** and from this sound field a beamwidth measure is determined **140**. This beamwidth measure relates to the beamwidth of the sound field as a function of frequency and its relationship to a specified dependence of beamwidth with frequency. Once the beamwidth measure is determined **140** the input parameters for the sound waveguide surface are varied **150** and re-inputted into parametric model **120**. Method steps **130**→**140**→**150**→**120** are then repeated in an optimisation loop until the beamwidth measure criterion is satisfied resulting in an optimised acoustic waveguide surface **160** designed according to the required beamwidth frequency dependence.

Referring now to FIG. **2**, there is shown a sectional profile of the shape of the sound waveguide surface which in this illustrative embodiment is defined as an axially symmetric horn **800**. The variation in the shape of the horn **800** is controlled by four independent parameters defined in relation to the horn mouth radius R_m which is the distance between points **200** and **210**. The distance R_m is fixed for design purposes and all other parameters (including frequency) are scaled to this dimension. The four independent parameters include:

1. the horn throat radius R_t defined as the distance between points **220** and **230**,
2. the horn length L defined as the distance between points **200** and **220**,
3. the distance x_1 defined as the fractional distance of point **250** along the line between points **240** and **260**; and
4. the distance x_2 defined as the fractional distance of point **280** along the line between points **270** and **290**.

In this illustrative embodiment, the fractional distances of points **240** and **270** along the line between points **230** and **210** are ⅛ and ⅔ respectively.

Point **300** lies vertically in line with point **240** and horizontally in line with point **200**. Similarly point **290** lies vertically in line with point **270** and horizontally in line with point **200**. Point **260** lies ½ of the distance between point **240** and **300**. A spline is fitted through points **230**, **250**, **280** and **210** and forms the profile of the horn **800**. The initial and final slope of the spline at points **230** and **210** can optionally be controlled or be included as free parameters in the optimisation process. In this illustrative embodiment, the initial slope at point **230** or at the throat of the horn **800** is defined to be 90° and the final slope at point **210** or at the mouth of the horn **800** is defined as 0°.

In practice any smooth curve formed through points **230**, **250**, **280** and **210** is sufficient. As depicted in FIG. **3**, a variety of horn profiles are achievable via this parameterisation. In this illustrative example the horn dimensional parameters of length L, throat radius R_t and mouth radius R_m are held constant and parameters x_1 and x_2 are allowed to vary as shown.

In this illustrative embodiment, the ANSYS® APDL command BSPLIN is employed to generate the horn profile. As is well known in the art, ANSYS® is a computational numerical