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TITLE:

METHOD AND APPARATUS FOR LOCATING BENDING WAVE TRANSDUCER MEANS

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DESCRIPTION15 FIELD OF INVENTION

The invention relates to achieving acoustic operation relying on bending wave action in typically panel-form members.

BACKGROUND TO INVENTION

20 For revelatory patent teaching regarding panel-form acoustic devices relying on bending wave action involving resonant modes of vibration, reference is directed to International patent application W097/09842. The latter teaches choice of parameters including shapes and bending
25 stiffnesses of particular panel-form members to optimise or at least improve acoustic behaviour, whether as a whole or for some part thereof to be acoustically operative, and specifically by reason of favourable distribution of resonant modes of bending wave vibration; and further

teaches favourable positioning of bending wave transducer means, specifically vibration exciter(s) in or on resonant panel member(s) of active acoustic device(s) such as loudspeaker(s).

5 By and large, teaching in W097/09842 is readily used for deterministic calculation in design of resonant mode bending wave action active acoustic devices, including loudspeakers, especially where panel-form members to be operative as a whole are of fairly simple readily
10 analysable shape/geometry, such as substantially rectangular; and are substantially isotropic or shape-related anisotropic as to bending stiffness(es), say resolving to substantially constant along main axes such as of length and width. Other patent applications by New
15 Transducers Limited, including PCT/GB98/00621 and a new PCT application, priority GB 9807316.6, disclose other design strategies, and viable variations of optimised transducer location(s) and/or panel geometry and/or distribution(s) of bending stiffness(es) and/or mass.

20 However, where the geometry of a panel-form member is relatively complex and/or not as normally hitherto considered favourable to resonant mode bending wave acoustic action, perhaps even has localised variations of thickness and/or out-of-planar curvature(s); and/or the
25 member is otherwise awkwardly anisotropic as to bending stiffness(es); and/or where only a part is to be or can be acoustically effective - then deterministic analysis/calculation can become more difficult and/or time-consuming, even practically impossible. Such circumstances

typically apply where some panel-form member is specifically for some other purpose but is of a material structure capable of bending wave action, and/or is acceptably modifiable in such respect, including
5 acceptably replaceable in whole or in part by such material structure, but best or acceptably satisfactory transducer location is unknown and not obvious.

It is also the case that above deterministic distributed mode principles establish feasibility of, and
10 enable, highly beneficial design of panel structures with appropriate excitation to operate by bending wave action over a remarkably wide acoustic bandwidth, say up to 8 octaves of frequency and between sensible amplitude limits.

15 However, there are many audio and acoustic applications that neither require nor in reality for practical purposes benefit from such a wide operating bandwidth; and/or may not require an optimal power response aimed towards best achievable constancy with
20 frequency. Examples arise in vehicle environments, including for acceptably satisfactory acoustic excitation of trim components, such as of doors, fascias, roof linings, shelf panels, etc. Indeed, in vehicle environments, placement of audio reproducing devices,
25 their physical relationship to the occupants, the specific acoustics of vehicle interiors, and desirable/ acceptable distribution of generated acoustic output power within a vehicle may indicate a viable, even preferable, frequency response from one or more panels as sound reproducer(s)

which is deliberately non-flat, for example, falling progressively with frequency. Other examples arise in other environments including of built-in panelling or cladding of what could be considered as generally of an architectural nature, or of such as furniture, or of displays such as hoardings or notice-boards, or whatever. Loudspeaker products for public address and/or combined display use may, of course, work perfectly adequately with a less uniform and less extended frequency range. Good speech intelligibility for a such as a poster panel or cladding member could require little if any more than 3 octaves of frequency bandwidth, say 500Hz to 4kHz.

SUMMARY OF INVENTION

The present invention resides in achieving distributed mode acoustic operation by and/or conforming with results of alternative and systematically empirical determination of beneficial location(s) as site(s) for one or more transducer means, specifically vibration exciter(s), in or on some chosen or given member of whatever geometry but of material structure capable of resonant mode based acoustically significant bending wave vibration.

According to one aspect of this invention, there is provided a method of determining beneficial site(s) for locating bending wave transducer means to be associated with member(s) for acoustic operation relying on resonant modes of bending wave action in such member(s), the method comprising investigative excitation of acoustically relevant bending wave action in a said member, and

systematic assessment of measurable effect(s) related to such excited bending wave action and corresponding said acoustic action as varying with bending wave transducer location areally of said member concerned.

5 Such investigative excitation may be by application of acoustic energy to said member concerned so as to induce said acoustically relevant bending wave action, say involving bending wave transducer means selectively operatively associatable areally locally of said member
10 concerned so as to respond to said acoustically relevant bending wave action.

 Alternatively, such investigative excitation may be by bending wave transducer means selectively operatively associatable areally locally of said member concerned so
15 as to induce said acoustically relevant bending wave action. Said systematic assessment may be of acoustic output of said member concerned, utilise said measurable effect being a parameter of said acoustic output, and said
20 acoustic output may be measured as to power and/or as to frequency content on a single point/axis basis or on a multi-point/axes basis for which measuring may be subjected to spatial averaging.

 Said systematic assessment may otherwise, indeed generally, be of signals in said transducer means for said
25 investigative excitation, including input signals thereto, utilised said measurable effect involving a parameter of said signals; and may be by analysis of input signal power and at least by implication power taken into said member from said transducer means, said measurable parameter

being of said signal input power and/or said power taken.

Said systematic assessment can readily and advantageously further comprise comparing said measurable effect for different areally local operative associations of said bending wave transducer means with said member concerned so as to aid selecting a said beneficial site.

Required operative association of said bending wave transducer means with said member concerned may involve temporary and variable location of contact effective as required relative to said acoustically relevant bending wave action; say with said bending wave transducer means making said effective contact during sliding over area of said member concerned for at least first selection of location(s) promising as a said site, and/or with said bending wave transducer means selectively fixed to said member-concerned for at least later stage(s) of selection of a said site.

Said investigative excitation may involve at least one of so-called pink noise, music and voice signals, in many cases all three.

Viable alternative systematic assessment(s) of measurable effect(s), i.e. other than relative to acoustic output of said member, include systematic assessment of the member itself, say in terms of measurable effect(s) such as mechanical impedance, typically at position(s) of excitation of bending wave action; and/or mechanical power, typically mechanical input power on the basis that acoustic power is usefully related as generally established in PCT/GB99/xxxxxx; and/or velocity involved

in excitation; and/or average velocity of bending waves in the member, though this tends to be most readily measured by rather expensive equipment such as involving scanning wavespeed or velocity probes such as laser surface vibration scanning systems. It is actually particularly advantageous to utilise analysis of signals at the excitation transducer means, say specifically in assessing related, mechanical impedance from which power and wavespeed/velocity can be calculated given knowledge of parameter of the excitation transducer means used.

However, specific description will be given of various methods including direct measurement of impedance using a piezo-electric impedance head; effective bending wave velocity assessment from voltage at terminals of a second transducer means placed in registration with the exciting transducer means but on the opposite side of the member; and laser measurement of wavespeed in the member along with using lumped-parameter modelling of the bending wave transducer means used.

Moreover, a said member may be investigated in relation to its own parameters, such as bending stiffness, as may be done using spaced excitation and sensing transducer means, including using two variably spaced excitation transducer means one of which may be of fixed and the other of variable position; and/or as to reverberation, as may be done using two excitation transducer means as above in registration on opposite sides of the member; but assessing relative to time response rather than mechanical impedance, time response

being the Fourier transform of frequency response, and resulting impulse response being used to plot energy in the member as a function of time; and/or coincidence frequency thus directionality effects for the member, as
5 may involve determining bending wave vibration wavelength of the member as a function of frequency, say from an image of the vibration pattern in the member obtained using scanning laser systems for wavespeed/velocity. Such investigations are of particular value where the member is
10 capable of modification, typically structural variation(s) in terms of adjusting effective bending stiffness or quality factor Q of intended acoustically active area or sub-area.

Alternative determination of frequency response may,
15 of course, always be by assessment of acoustic output from the member as to frequency content, as may be done in anechoic conditions in order to avoid confusion with reverberation effects of a room.

Other features investigatable by methods hereof
20 include relevant parameters of excitation transducer means, such as size, say to avoid intrusive resonance associated with bending wave vibration wavelength relative size of excitation transducer means, particularly where those are comparable, and so-called 'aperture' effects
25 arise, and also as assessable using laser scanner imaging.

BRIEF DESCRIPTION OF DRAWINGS

Exemplary implementation will now be described with reference to the accompanying diagrammatic drawings, in which:

Figure 1 shows investigation of a car interior door panel (10);

Figure 2 shows potentially useful sub-areal indication for another vehicle door trim panel;

5 Figures 3A, B indicate automated co-ordination of scanning;

Figures 4A, B give idealised graphical indication(s) for exciter impedance analysis;

10 Figures 5A, B relate to equalisation as applied to a particular panel member;

Figure 6 is an outline schematic for a panel member excited by acoustic power and with a roving bending wave sensing transducer;

15 Figure 7 is an outline schematic for direct measurement of mechanical impedance;

Figures 8A and B, C are related graphical indications of mechanical impedance and derived power and excitation velocity, respectively with frequency;

20 Figures 9A, B are partial plots of inverse mean square deviation of mechanical impedance and mechanical power, respectively, to indicate most viable drive positions;

Figures 10A,B are graphical indications of mechanical power for good and poor excitation locations;

25 Figure 11 is an outline schematic for use of an opposed pair of excitation and sensing transducer means;

Figure 12 is a lumped electrical equivalent circuit for taking account of excitation transducer parameters;

Figure 13 is a graphical indication of impedance

using laser velocity scanning system;

Figure 14 is a graphical indication of mechanical impedance relevant to Figure 11;

Figures 15A, B are graphical indications of bending wave wavelength and velocity with frequency by a laser scanning system to indicate coincidence frequency;

Figure 16 is a vibration pattern plot for one frequency as obtained by laser scanning;

Figures 17A, B are outline schematics for member excitation and microphone or sensing transducer input to a standard MLSSA system;

Figure 18A,B,C,D are exemplary plots of waterfall and Schroeder nature, together with damping ratio and Q-factor indications.

Figure 19 is a schematic for a jig to facilitate assessment using spaced transducer means; and

Figure 20 is a resulting graphical representation from which bending stiffness is calculable.

DESCRIPTION OF ILLUSTRATED EMBODIMENTS

In Figure 1, the car door panel (10) is of complex shape including upper out-of-plane curvature at least at 11A, 11B, 11C, 11D and 11E, and a storage fitting at (12). The central area (15) may also have intrusions of various types, but will probably represent a reasonable target area for distributed mode loudspeaker operation. An alternative might be the upper minor area (16), at least if sufficiently flat (though curved panels can work as noted in others of our patent applications).

It can be useful for the purposes hereof to visualise

a likely sub-area or sub-areas, say by way of imposing, or visualising circular, elliptical and rectangular shapes, included in the target area (15 or 16). Such sub-area(s) could be marked out, but is/are readily simply envisaged
5 by a skilled operator. Then, positions such as geometrical centres or foci can readily be discarded, often in lines or curves of such sub-areas. Edge positions of the envisaged sub-area(s) would also be unlikely candidates. Indeed, the sort of off-set from centres/foci and edges
10 that arise on our above PCT and other applications can readily be approximated; and, as a kind of often useful pre-selection, an excitation transducer (20) applied thereto on a roving basis, say with pink noise selected from audio source (24).

15 Acoustic results from the panel (10) are readily continuously analysed by pick-up at microphone (26) and feeding to programmed analyser (30), which may be programmed to indicate quality at least on a series of threshold bases. Once some promising site(s) is/are
20 located, the excitation transducer (20) can be stuck down using acoustically coupling double-sided tape; and further investigation carried out, including selection of voice and familiar music audio signals.

The analyser (30) may conveniently de-select
25 positions that have dominant coupling to only a few resonant frequencies; and favourably indicate positions effectively having a relatively neutral coupling to resonant mode frequencies, including preferably free of any significant dominance by only one, two or a few

frequencies. Such positions of neutrality, often area(s) therefor, typically of strip(s)-like nature are found to be relatively promising by reason of having likely coupling to many if not most, even at least approaching
5 all, resonant mode frequencies (at least on a combination basis for two or more positions).

Figure 2 shows another vehicle door trim panel member 210 and a sub-area 215 shown shaded as promising for finding somewhere effective for exciter transducer
10 mounting. It will be appreciated that vehicle trim parts, whether or not related to doors (e.g. parcel shelf, seat back or even headliner), may well generally have material composition (as well as geometry) that is not ideal for a distributed mode loudspeaker, often heavier. However,
15 useful acoustic vibration is often feasible and areas of useful distributed mode operation usually identifiable using the systematic procedures hereof. Frequency characteristics less uniform than for purpose-designed distributed mode panel loudspeaker members encourage
20 electrical and/or mechanical equalisation adjustment in fairly straight-forward manner, including taking account of such as in-vehicle frequency characteristics.

Figure 3A can be seen as indicating a systematically co-ordinated scanning scheme, say essentially following
25 orthogonal X, Y co-ordinate values as successive line scans, though in practice it is sufficient merely for the position of the roving transducer always to be known relative to a start reference position on the panel member concerned. Figure 3B shows panel member 310, exciter 320

and positional drive 330 that can be of motorised arm and incremental stepper motor type to cover an X, Y region as in Figure 3A, typically under appropriate micro-computer control 331.

5 Figure 3B is actually based on analysis of electrical input impedance of an electrodynamic, moving coil type, excitation transducer 320. Such impedance contributions then characteristically comprise resistance and inductance of the drive coil along with smaller element dependent on
10 modal vibration behaviour of the panel member 310 as energised by the transducer 320 for any instantaneous transducer position. Figure 3B thus indicates microcomputer control at 331 for transducer drive from 332 via drive amplifier 333; and sampling from resistor 334 at
15 335 for signal conditioning at 336 to remove static exciter coil contributions and leave dynamic modal vibration components using current/voltage ratio and obtaining information as to modal characteristics and density, see also smoothed exciter impedance/frequency in
20 Figure 4A and magnified dynamic modal distribution in Figure 4B. Poor modal distribution corresponds to uneven vibrational behaviour and greater variation of impedance, so that lesser impedance variation represents more even modal density and distribution, thus is sought as a
25 measure of quality, specifically as indicated derived at 337 under programmed micro-computer control (331). In terms of useful output, full or appropriately pre-selected data is made available, see at 338 and further at 339A, B for such as distributed mode bandwidth/quality indication,

optimal exciter co-ordinates, respectively.

Figures 5A and 5B are useful in terms of indicating at P sound level variation with frequency for a panel member such as of vehicle trim nature and at E generally compensatory equalisation, and simple serial two-stage R-C equaliser circuitry 540A, B for such a panel member and two exciter transducers 520A, B in parallel.

Generally similar considerations apply to systematic assessment as applied to signals in a transducer used for sensing purposes where the panel-form member concerned has bending wave vibration induced therein by means other than an excitation transducer. Best position(s) in terms of sensed signals will correspond to where an excitation transducer should be placed for best results. Figure 6 shows outline system for producing substantial acoustic power sufficient to so energise a panel-form member, see acoustic signal source 624 and acoustic output device 625, which could be of well-known conventional cone-type (say, but not necessarily a single mid-range unit), and roving sensing bending wave vibration transducer 620 to analyser 630 relative to panel member 610, which could again be a vehicle interior trim panel or any other panel-form member to be investigated (as outlined above) and thus shown only partially with extent beyond some pre-selected promising sub-area (cross-hatched) omitted.

Systematic assessments of other usefully measurable effects are now considered relative to a panel-form member as such and/or to signals of excitation and/or sensing transducer means, regardless of the purpose of the panel-

form member.

Figure 7 shows outline for a form of impedance head system for measuring mechanical impedance based on standard mechanical engineering techniques. Two piezo-electric transducers 721, 722 are shown together with a vibration applicator or shaker 723 with associated force-transmitting and directing shaft 724 and sensing tip 725. One of the transducers 721 serves to measure applied force by way of the sensing tip 725 and the other transducer 722 serves as an accelerometer to measure movement of the panel member concerned. The transfer function $T(\omega)$ of force/velocity is related to mechanical impedance. Outputs from the transducers 721, 722 are in relation to charge, and are shown conditioned by a typically high impedance charge amplifier 726 serving to convert to a voltage for feeding into a Fourier transform analyser 730 - which may be of stand-alone or PC-integrated system type and will typically be of two-channel nature producing a measure of the transfer function $T(\omega)$ as a ratio of force $F(\omega)$ and velocity indication from the accelerometer $A(\omega)$.

The force measure $F(\omega)$ can readily be corrected for contribution from inertial forces of the sensing tip 725, basically by subtraction to give true force from the member $TF(\omega) = F(\omega) - M.A(\omega)$ where M is the mass of the sensing tip. The velocity $V(\omega)$ is derived from the acceleration $A(\omega)$ by scaling using angular frequency, as $V(\omega) = A(\omega)/i\omega$; and mechanical impedance $Z_m(\omega)$ of the

member will be

$$Z_m(\omega) = i\omega\{T(\omega) - M\}$$

i.e. is readily derived simply from measurement of the transfer function $T(\omega)$ and knowledge of the tip mass M .

5 It will be appreciated that the sensing tip mass M effectively places an upper limit on measurable frequency; and it becomes progressively more difficult and less accurate to extract true force from combined force as inertial forces of the sensing tip approach comparability
10 with the forces of interest for the member. Accordingly, an upper frequency limit is usefully set for this implementation of systematic assessment, say by reference to such inertial forces $F(I)$ being no more than twice the member forces of interest (F_m) resulting in practical
15 upper frequency limit represented by $2.Z_m/M$. It will also be appreciated that mechanical impedance can become very small at particular resonant bending wave mode frequencies of the member, especially for a low loss said member, and account should preferably be taken of resulting
20 measurement sensitivity to peaks in mechanical impedance of the member between its resonant modes, and consequential clipping of minima of Z_m .

Figure 8A shows exemplary measurement of modulus mechanical impedance for a panel member portion of
25 interest, typically a flat region medially of the panel member, say as shaded in Figure 2. Figures 8B, C show corresponding mechanical input power and excitation position velocity, respectively, as derived from the

measurements of Figure 8A with knowledge of excitation transducer parameters. All have similar variational characteristics and so are equally viable in determining best or satisfactory excitation transducer position(s), typically by systematically varying test positions over the portion of the member of interest, say as hatched in Figure 2. A relatively coarse grid of such positions may be followed by a finer grid relative promising coarse grid positions. Preferably, the measured or derived mechanical impedance is subjected to third octave smoothing and then fitted to a reference value or flat line, say using inverse of mean square deviation over a desired frequency range, say 200Hz to 5kHz as a measure of satisfactory effectiveness. For convenience only, representation is shown in Figure 9A as though for a quarter-panel plot relative to a substantially rectangular panel member - say used notionally as above in conjunction with inspection to identify such potential - but the co-ordinate boundaries should not be taken as necessarily corresponding to all of available portion of a panel member of potential interest (which may not be substantially rectangular). The lightest region is seen as of greatest promise for excitation transducer location; and correlation with medial but near to central eccentricity is satisfyingly consistent with the massive body of experimentation and theoretical analysis built up for special purpose wholly active acoustic panel members. This is reinforced by the similar plot of Figure 9B obtained from systematic assessment of mechanical power also fitted to a straight line. It will

be appreciated that variations are to be expected according to frequency and according to the function used or required for the fitting to a straight line; indeed, can readily be deliberately invited by imposition on such
 5 function of variation of frequency established as beneficial to particular applications, such as in-vehicle environments discussed above.

Figures 10A and 10B give indications of mechanical input power results for good and poor positions for
 10 excitation transducer means, and are presented mainly as guides to the systematic assessment taught herein.

It is, of course, the case that motion of the panel member is only weakly transferred to the electrical part of the excitation transducer means, thus indicating low
 15 sensitivity of the transducer means impedance to sensing wave velocity in the panel member, actually being most evident in excitation transducer resistance when motion of the panel member is greatest. It follows that accuracy of determination of the mechanical impedance of the panel
 20 member should be enhanced by more sensitive measurement of exciter velocity in the panel member, as available (albeit rather expensively) from laser scanning systems. Weak feed-back of such wavespeed/velocity into the force applied to the panel-form member can then be overcome and
 25 accurate determination of the whole network facilitated using a relationship for the force involving the ratio of $(i\omega M_{mm}V)/Bl$ plus product of wavespeed/velocity with

$$[(R + i\omega L) \omega^2 M_{mm} M_{ms}] / (Bl)^2$$

less product of wavespeed velocity with
 $i\omega(M_{ms} + M_{mn}) \{1 + [(R + i\omega L)/(Bl)^2] \cdot [R_{ms} + 1/i\omega C_{ms}] \}$
 and $1 + [(R + i\omega L)/(Bl)^2] \cdot [R_{ms} + 1/i\omega C_{ms} + i\omega M_{mn}]$. Ratio
 of force and wavespeed/velocity then gives impedance of
 5 the panel member most accurately. Figure 13 shows
 resulting mechanical impedance for a particular car door
 panel.

Figure 11 relates to notably inexpensive and highly
 effective investigation using a pair of transducer means
 10 111, 112 in registration as to effective coupling to
 opposite sides of a panel form member 113. One transducer
 means 111 serves for bending wave excitation in the member
 113, see excitation signal input lines 115 from source
 116; and the other transducer means 112 serves for sensing
 15 resulting bending wave excitation, see connection 117 to
 Fourier transform analysis equipment 118. The voltage at
 the terminals of the sensing transducer means 112 is
 directly related to the exciter velocity in the panel
 member 113 (see further below), and the wavespeed/velocity
 20 result can be used as elsewhere herein, say specifically
 in the following way relative to impedance of excitation
 transducer means.

Standard inertial vibration excitation transducers
 can be accurately represented and modelled by a lumped
 25 parameter network of masses, springs and dashpots for the
 mechanical parts and inductors, capacitors and resistors
 for the electrical contribution- leading to the combined
 lumped parameter equivalent electrical circuit of Figure

12. In Figure 12, R and L are voice coil resistance and inductance, B_l is electrical-to-mechanical conversion factor M_{mm} and M_{ms} are masses of magnet cup and voice coil, and C_{ms} and R_{ms} represent compliance and resistance of voice coil suspension, Z_m being mechanical impedance of interest for the panel member concerned.

The velocity relationship referred to above is $(v/B_l) \{ (i\omega M_{ms} + R_{ms} + 1/i\omega C_{ms}) / i\omega M_{mm} \}$ and the equivalent circuit of Figure 12 is readily solved by measuring voltage and current for the excitation transducer means, thus effectively knowing the impedance of that transducer means. This method is highly effective for a good approximation to the force applied to the panel member as represented by voltage across the impedance of the panel member.

Interestingly, the mechanical impedance of Figure 14 for the same panel without such correction demonstrates the effectiveness of the latter, as will be apparent from remarkably close similarity of Figures 13 and 14.

Use of laser scanning systems can be further or alternatively useful for determining wavelengths of bending wave vibration in panel members, by way of imaging bending wave vibration patterns in the panel member, typically on a per excitation frequency basis at any one time. The result of successive such imaging represents bending wave velocity and wavelength as a function of frequency, see Figures 15A, B, noting that for coincidence the wavespeed in air is 343 m/s. A particular useful

result is identifying coincidence frequency, specifically at about 15 kHz for Figures 15A, B. An example of panel member vibration at 5 kHz is given in Figure 16, from which it is noteworthy that the pattern is substantially circular from the excitation position, and which itself indicates that the acoustically active area of the panel member is sufficiently large and effectively reasonably well damped for there to be no boundary reflections that significantly interfere with the vibration as excited. The wavelength is thus very readily revealed from Figure 16. If the imaged pattern is more complex, as may well be the case for different areal boundary conditions and lower frequencies of excitation, a range of measurements of apparent wavelength could be made on the same resulting image, and then averaged, alternatively a spatial Fourier transform could be made of the complex data image.

As to size of excitation transducer means, another requirement is, of course, relative to desired frequency range of acoustic operation, e.g. for operation in a range up to 10 kHz the transducer size must be less than 28mm in its areal dimensions.

Another factor that it can be useful to investigate by systematic assessment is as to damping properties of the panel member concerned, thus related Q-factor; and same is achievable by investigation of reverberation time data. Figures 17A, B show two system set-ups usable in conjunction with standard MLSSA signal processing. Figure 17A shows panel member 171 with variable position excitation transducer 172 fed from amplifier 173, and

microphone 174 for at least single-axis sensing of acoustic output from bending wave action in the panel member 171 and feeding MLSSA System 175 via pre-amplifying means 176. It will be appreciated that the microphone 174
5 could be of a line or matrix array for planar and/or multi-axes sensing and assessment of acoustic output. Figure 17B shows alternative sensing via further transducer 177 shown in registration with the excitation transducer 172 and on the opposite side of the panel
10 member 171, thereby avoiding need for use of an anechoic chamber as normal for Figure 17A. In addition for Q measurement the sensing transducer may also be placed at other points other than in precise registration with the drive transducer.

15 Standard operation capabilities of the MLSSA system 175 is effective to measure impulse response of the vibrating panel member 171 and evaluate damping and Q-factor, typically using so-called water-fall plot and/or Schroeder filter view modes of operation, the former as an
20 energy/time/frequency function readily affording indication of number of cycles (N) to be monitored for particular energy decay (say to a particular level or by a particular percentage), the latter for energy decay for a selected frequency to which the Schroeder filter centre
25 will correspond; the procedure affording accurate calculation of given decay, typically by 60dB.

One example of this systematic assessment evaluation involves damping ratio (D), particularly its logarithmic decrement ($d = 2\pi D$) as a measure of how fast bending wave

vibrations decay in the panel member, and uses the equation $d = 1/N \cdot \ln(x_i/x_n)$, where x_i is first detected amplitude of vibration and x_n is amplitude at Nth cycle; and further involves Q-factor measure as the ratio of displacement amplitude at resonance and static displacement for the same applied force, and related to the damping ratio as $Q=1/2D$. Effectively, above-noted requirement for determinations from system response to applied force, as available from impulse or frequency response as measured under anechoic conditions or directly measured by laser scanning, can be replaced by standard MLSSA processing using the sensing transducer means 177.

For panel members intended for some purpose other than acoustic operation by bending wave action, particularly at some sub-area position(s) only thereof, bending stiffness may well not be known; and it is thus beneficial to be able to calculate, especially using techniques relying on systematic assessment of excited bending wave action. An advantageous way of doing so arises from relating wave-length, in the panel member at a given frequency with surface density and material bending stiffness of the panel member, as $B(f, \lambda, \mu) = (f^2 \cdot \lambda^2 / 4 \cdot \pi^2) \cdot \mu$; and relying upon finding the separation between two excitation bending wave transducer means at which destructive superposition occurs, which will correspond to one-half wavelength of the frequency concerned.

Figure 19 shows outline of a jig 191 by means of which bending wave transducers are variably associatable

with the panel member concerned. Locations represented by circles (1-6 and A) are for a sensing transducer at location A and excitation transducers at two of the other positions, specifically at location 6 and at one of
5 locations 1-5. The different spacings between locations 6 and the locations 1-5 permit bending stiffness (B) to be calculated at different frequencies. The investigative methodology involved comprises first measuring sensed panel member bending wave action when only the excitation
10 transducer at location 6 is energised as indicative of the panel member transfer function and showing excited resonant modes of the bending wave action in the panel member; and secondly measuring sensing transducer output with both of the excitation transducers energised, which
15 is preferably with electrical connection in parallel to reduce inertial effects and will produce a somewhat different panel member transfer function by reason of different resonant modes excited and with superposition effects as a multiplication factor. Subtracting the first
20 result from the second result on a dB scale reduces effect of the panel member transfer function and a relative dip is observable at the cancellation or destructive superposition region.

An exemplary result is shown in Figure 20 for a 19mm
25 separation of excitation transducers and a panel member with μ of 1.05 kilogram per square metre, revealing a dip at 15 kHz thus wavelength (λ) of 2.19 mm and frequency (f) of 15kHz; thus calculated panel member bending stiffness

of 12.48 Newtonmetres.

The invention effectively provides method(s) for any panel-form member to operate as a diffuse sound radiator if such is feasible and based on distribution of resonant modes of bending wave vibration, but with this objective achieved empirically by systematic assessment methodology hereof. Such approach can be used for simple panel shapes by anyone for any reason not wishing or capable of using our deterministic mathematical methodology and solutions provide good predictable results, and provides solutions for complex shapes that could not be mathematically deterministically achieved without very extensive and complex use of finite element analysis (FEA) that would require prodigious data preparation and processing capabilities, including available computing power. The indicated potential is high (and of great practical value) for whole processes hereof to be automated, particularly in using a kind of error reduction scheme to arrive at an optimised excitation transducer location(s) for given panel-form member(s).

Algorithms etc now follow, as in the above-mentioned PCT/GB99/xxxxx for use in further assessing the quality of the final object through the measurement of impedance and frequency response.

More specifically, spread of frequencies of natural resonant modes for an acoustic panel member is readily investigated by use of central differencing analysis, viz:

$$SEE(A) = \sqrt{\frac{1}{last(A)-3} \sum_{n=1}^{last(A)-1} (A_{n+1} + A_{n-1} - 2.A_n)^2}$$

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where A_n are resonant mode frequencies (eigenvalues) in ascending order.

Appropriate refinement regarding investigating spread of resonant mode frequencies can include considering useful sub-groupings according to some characteristic, say of a nature involving symmetry. For example, for substantially rectangular acoustic panel members, and at least relative to orthogonal beam simplification, the SEE measure could be in relation to odd-odd, even-even, odd-even and even-odd sub-groups of resonant modes individually for such sub-groups and collectively by weighted summing, viz:

$$F_{moo}(\alpha) := A \frac{\text{No.} \frac{p_o - 1}{2} + \frac{q_o - 1}{2}}{\text{sort}(A)} \leftarrow f_m(\alpha, p_o, q_o)$$

$$F_{mee}(\alpha) := A \frac{\text{Ne.} \frac{p_e}{2} + \frac{q_e}{2}}{\text{sort}(A)} \leftarrow f_m(\alpha, p_e, q_e)$$

$$F_{mix1}(\alpha) := A \frac{\text{Ne.} \frac{p_o - 1}{2} + \frac{q_e}{2}}{\text{sort}(A)} \leftarrow f_m(\alpha, p_o, q_e)$$

$$F_{mix2}(\alpha) := B \frac{\text{No.} \frac{p_e}{2} + \frac{q_o - 1}{2}}{\text{sort}(B)} \leftarrow f_m(\alpha, p_e, q_o)$$

$$\text{SEW}(\alpha, a, b, c, d) := \frac{a \cdot \text{SEE}(F_{moo}(\alpha)) + b \cdot \text{SEE}(F_{mee}(\alpha)) + c \cdot \text{SEE}(F_{mix1}(\alpha)) + d \cdot \text{SEE}(F_{mix2}(\alpha))}{a + b + c + d}$$

The values of frequencies of natural resonant modes and their distribution or spread depend on materials/structure and geometry/configuration of panel members concerned; and indicate suitability for acoustic device application, for which evenness of spread/distribution is established as being particularly beneficial. There is, of course, no account taken of transducer location at this stage.

For known resonant mode frequencies and corresponding shapes of bending wave vibration can also be modelled, the mechanical admittance can be investigated for any particular transducer location, viz:

$$Z_m = \frac{\mu m^2}{j\omega \left[\sum_p \sum_q \left(\frac{Z(p, \xi_0)}{C_p} \right)^2 \left(\frac{Z(q, \eta_0)}{C_q} \right)^2 \cdot \frac{1}{\omega_{pq}^2 - \omega^2} \right]}$$

$$Y_m(\omega) = j\omega \left[\sum_p \sum_q \frac{Y_{p,q}}{\left[\left(\omega_{p,q} \right)^2 - \omega^2 \right] + 2j\zeta_{p,q} \omega_{p,q} \omega} \right]$$

where $Y_{p,q}$ is the square of the amplitude of the mode shape at the transducer location concerned, and represents an amount of damping. Plotting a log-log graph can facilitate finding smoothest response, or the root mean square deviation can be investigated over a specified range, say for minima of

$$\sigma(\alpha, \xi, \eta) = \sqrt{\frac{1}{sx} \left[\sum_i x_i \left(\log \left(|Y_m(x_i, \alpha, \xi, \eta)| \right) \right)^2 \right]}$$

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or of

$$\sigma(\alpha, \xi, \eta) = \sqrt{\frac{1}{sx} \left[\sum_i x_i \left(W_i \log \left(|Y_m(x_i, \alpha, \xi, \eta)| \right) \right)^2 \right]}$$

representing application of a weighting function.

Where the resonant mode frequencies are known, but
 5 not the corresponding vibration shapes (or same not
 modelled and taken into account by choice, investigation
 of intrinsic mechanical impedance can be investigated
 using the formulae

$$Y_m'(\omega) = j\omega \left[\sum_p \sum_q \frac{Y_{p,q}}{\left[\left(\omega m_{p,q} \right)^2 - \omega^2 \right] + 2j\zeta_{p,q} \omega m_{p,q}} \right]$$

$$\sigma'(\alpha, \xi, \eta) = \sqrt{\frac{1}{sx} \left[\sum_i x_i \left(W_i \log \left(|Y_m'(x_i, \alpha, \xi, \eta)| \right) \right)^2 \right]}$$

10 which can be done without reference to any particular
 transducer location by setting $Y_{p,q}$ to unity. Results will
 not be as accurate as for mechanical admittance taking
 account of transducer location, and will be slower than
 above investigation of mechanical admittance.

CLAIMS

1. Method of determining beneficial site(s) for locating bending wave transducer means in operative association with member(s) relying for acoustic operation on resonant modes of bending wave action in such member(s), the method comprising investigative excitation of acoustically relevant bending wave action in a said member and systematic assessment of measurable effect(s) related to such excited bending wave action and corresponding said acoustic action, which effects vary according to bending wave transducer location areally of said member concerned
2. Method according to claim 1, wherein said investigative excitation is by application of acoustic energy to said member concerned so as to induce said acoustically relevant bending wave action.
3. Method according to claim 2, wherein said systematic assessment involves bending wave transducer means selectively operatively associatable areally locally of said member concerned so as to respond to said acoustically relevant bending wave action, said measurable effects being of signals from said transducer means.
4. Method according to claim 1, wherein said investigative excitation is by bending wave transducer means selectively operatively associatable areally locally of said member concerned so as to induce said acoustically relevant bending wave action.
5. Method according to claim 4, wherein said systematic assessment is of acoustic output of said member concerned, utilised said measurable effect being a parameter of said

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acoustic output.

6. Method according to claim 5, wherein said acoustic output is measured as to level on a single point/axis basis.
- 5 7. Method according to claim 5 or claim 6, wherein said acoustic output is measured as to frequency content on a single point/axis basis.
8. Method according to claim 5, 6 or 7, wherein said acoustic output is measured as to power on a multi-
- 10 point/axes basis.
9. Method according to any one of claims 5 to 8, wherein said acoustic output is measured as to frequency content on a multi-point/axis basis.
10. Method according to claim 8 or claim 9, wherein said
- 15 multi-point/axes measuring is subjected to spatial averaging.
11. Method according to claim 4, wherein said systematic assessment is of input signals to said transducer means for said investigative excitation, utilised said
- 20 measurable effect involving a parameter of said input signals.
12. Method according to claim 11, wherein said systematic assessment of said input signals is by analysis of input signal power and at least by implication power taken into
- 25 said member from said transducer means, said measurable parameter being of said signal input power and/or said power taken.
13. Method according to claim 4, wherein said systematic assessment is of signals from sensing means responsive to

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the induced bending wave action.

14. Method according to claim 13, wherein said sensing means comprises another bending wave transducer means as associatable with said member.

5 15. Method according to claim 14, wherein said other transducer means is so associatable in registration with the first-mentioned transducer means, the two registering transducer means being operatively associated with opposite sides of panel-form said member.

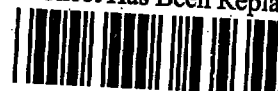
10 16. Method according to any one of claims 3 to 15, wherein said systematic assessment further comprises comparing said measurable effect for different areally local operative associations of said bending wave transducer means with said member concerned so as to aid
15 selecting a said beneficial site.

17. Method according to any one of claims 3 to 16, wherein required operative association of said bending wave transducer means with said member concerned involves temporary and variable location of contact effective as
20 required relative to said acoustically relevant bending wave action.

18. Method according to claim 17, wherein said bending wave transducer means makes said effective contact during sliding over area of said member concerned for at least
25 first selection of location(s) promising as a said site.

19. Method according to claim 17 or claim 18, wherein said bending wave transducer means is selectively fixed to said member concerned for at least later stage(s) of selection of a said site.

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20. Method according to any preceding claim, wherein said investigative excitation involves at least one of so-called pink noise, music and voice signals.
21. Method according to claim 1, wherein said systematic
5 assessment is by way of and in relation to signals from a piezo-electric impedance head device.
22. Method according to claim 21, wherein the impedance head device comprises two piezo-electric transducers with force-transmitting means from vibration applying means and
10 sensing tip means to engage said member, one of the piezo-electric transducers being responsive via said tip means to provide signals representative of force applied to said member and the other of the piezo-electric transducers being operative as an accelerometer provide signals
15 representative of vibration movement of said member by bending wave action, the signals from the piezo-electric transducers being processed according to force and velocity contents.
23. Method according to Claim 22, wherein processing of
20 said signals includes correction for contribution from inertial forces of the sensing tip means.
24. Method according to Claim 22 or claim 23, wherein said processing derives measure of mechanical impedance of said member.
25. Method according to claim 22, 23 or 24, wherein said
25 processing derives measure of mechanical power of said bending wave vibration.
26. Method according to any one of claims 22 to 25, wherein said systematic assessment is up to a frequency

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limit defined by twice the division of mechanical impedance by mass of the tip means.

27. Method according to any preceding claim, wherein said systematic assessment includes signal processing relative to parameter(s) of said transducer means.

28. Method according to any preceding claim, wherein said systematic assessment includes signal processing relative to a lumped electrical equivalent circuit for said transducer means.

29. Method according to any preceding claim, wherein said systematic assessment includes use of signals from laser scanning of said member in bending wave excitation.

30. Method according to claim 29, wherein processing of the laser scanning signals affords measure of wavespeed/velocity of bending wave vibration in said member.

31. Method according to claim 29 or claim 30, wherein processing of laser scanning signals affords measure of wavelength of bending wave vibration in said member.

32. Method according to claim 29, 30 or 31, wherein processing of laser scanning signals affords identifying of coincidence frequency for said member.

33. Method according to claim 1, wherein said systematic assessment includes investigation of damping and/or Q-factor for said member in bending wave vibration.

34. Method according to claim 33, wherein the systematic assessment includes investigation of reverberation time data for bending wave vibration in said member.

35. Method according to claim 34, wherein said systematic assessment includes processing of signals using MLSSA

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techniques applied to acoustic output of said member in bending wave vibration.

36. Method according to claim 33, 34 or 35, wherein said systematic assessment includes signal processing to
5 produce so-called waterfall plots and/or Schroeder filter views.

37. Method according to any one of claims 33 to 36, wherein said systematic assessment includes processing of signals relative to particular decay of bending wave
10 vibration energy.

38. Method according to claim 37, wherein said processing is for a number of cycles corresponding to energy decay of about 60 dB.

39. Method according to any one of claims 33 to 38,
15 wherein said systematic assessment includes signal processing relative to logarithmic decrement of damping ratio.

40. Method according to any preceding claim, wherein said systematic assessment includes determining bending
20 stiffness of said member at area thereof of interest for acoustic bending wave action.

41. Method according to claim 40, wherein the bending stiffness determination involves relating with wavelength of bending wave vibration in said member at given
25 frequency and surface density.

42. Method according to claim 40 or claim 41, wherein said member is excited into bending wave action by two transducer means for which actual or effective variable areal spacing is investigated to find spacing at which





there is destructive superposition and corresponding to one-half wave-length for the frequency concerned.

43. Method according to claim 42, wherein said two transducer means are energised through electrical
5 connection in parallel thereto.

44. Method according to claim 42 or claim 43, wherein a further bending wave transducer means is fixed spaced from the two bending wave transducer means and used for sensing purposes in providing signals representative of bending
10 wave vibration in said member.

45. Method according to claim 44, wherein one of the two transducer means is at a fixed spacing from the further transducer means and the other of the two transducer means is at further variable spacing.

46. Method according to claim 45, wherein said systematic assessment includes first sensing and deriving transfer function with only said one transducer means energised, second sensing and deriving transfer function with both of the two transducer means energised, subtracting result of
15 said first sensing result from result of said second sensing on a dB scale, and observing a relative dip indicative of destructive superposition frequency.

47. A method according to any preceding claim, wherein the systematic assessment includes application of acoustic
25 energy by means of a transducer placed sequentially at a plurality of candidate locations within a selected sub-area of the member.

48. A method according to any preceding claim, wherein the member is of irregular shape, thickness and/or

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stiffness.

49. A method of manufacturing a loudspeaker having a panel member and at least one bending wave transducer, including determining beneficial sites using a method
- 5 according to any preceding claim, providing a panel member, providing at least one bending wave transducer, and attaching the at least one transducer to at least one of the determined beneficial sites.
50. Apparatus arranged and adapted to operate to carry
- 10 out the method according to any preceding claim.

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