Architectural Acoustic Modeling of Ship Noise and Sound Field Mapping

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Programs used for ship sound level analysis and mapping (SLAM) have become increasingly refined over the years but still incorporate the basic elements of architectural acoustics. The important relationships and noise mechanisms modeled by these codes are reviewed along with more recent developments in the field of ship noise modeling. Also reviewed is the definition of equipment A-weighted sound power level (PWL_a) and a relatively new tool the author has developed and tested, defined here as the A-weighted room constant (R_a), a single-number rating system. When used together, these tools bring the free-field sound power level aboard ship to make useful A-weighted sound level predictions in semi-reverberant machinery spaces. This method has obvious applicability to mechanical rooms in large buildings and commercial and industrial structures. In addition, recent important publications in the field of ship noise control are briefly described, and suggestions are made for future research and development.

While computer programs used for noise work in naval architecture have become increasingly complex, they continue to employ the fundamental rules of architectural acoustics. These codes routinely incorporate local equipment noise emissions, ventilation noise and duct breakout noise as well as noise transmitted from adjacent noisy compartments. These well known techniques employ the large-room acoustic equations that assume the physical dimensions of the space are many multiples of the wavelengths of the noise being analyzed. When performed properly, these procedures are known to produce good agreement with measurements at midrange to high frequency (500 to 8000 Hz), where wavelength is small relative to the dimensions of a space.

Large-room acoustic equations are known to produce conservatively larger and louder predictions at lower frequencies and in smaller spaces, where wavelengths are in parity with or larger than compartment dimensions. This is only somewhat compensated for by the SNAME (Society of Naval Architects and Marine Engineers) method, which employs minimum room constants[1] at low frequencies. Single-figure, A-weighted, sound level criteria are currently used to specify compartment noise limits in most building specifications. This makes accuracy at low frequencies somewhat less critical, since the large negative A-corrections reduce the contributions of the lowest frequencies to total sound level.

Many ship specifications recommend the use of References 1 and 2, SNAME T&R 3-37 of 1983 and its more recent supplement of 2001, for ship airborne noise modeling and permit the use of these somewhat codified methods. In addition, References 3 and 4 have been cited for HVAC noise work and ventilation noise prediction. While current and prior ship specifications have supported these methods, they did not prohibit the use of more advanced methods if the ship builder felt them necessary.

Basic Architectural Acoustics Models

The *point* and *line* noise sources for equipment contained in Reference 5 remain the two fundamental direct-field modeling elements of architectural acoustics. The basic point source model exhibits inverse square ($1/r^2$) attenuation, and the line source demonstrates approximately cylindrical ($1/r$) spreading. The *distributed area* noise source model of Reference 6 is intended for large extended surfaces and incorporates a clever multi-surface model of the acoustic power radiated from the five large rectangular surfaces of a solid rectangular parallelepiped located over a reflecting plane. This model is considered representative of a shipboard gas turbine enclosure and was empirically justified by the three authors of Reference 6 by model testing in an anechoic chamber.

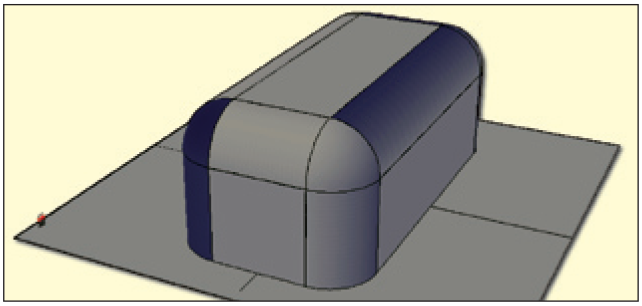

Figure 1. Noise radiation surface area of a rectangular solid source of acoustic power on a reflecting plane. (Dimensions obtained from Reference 6.)

Recommended Equipment Model

A point noise source model will be sufficiently accurate at standoffs greater than twice the major dimension of the equipment it represents. A point can be used for most small to medium-sized equipment like pumps, compressors, and purifiers, ranging in size from a fraction of a foot to a maximum of perhaps 5 feet in major dimensions. Modestly sized HVAC terminals that service a space and are direct noise sources may also be represented using the simple point source. Line sources need only be used to represent more linear equipment like HVAC duct breakout noise transmitted along the length of the duct and larger equipment like refrigerators, turbines, and diesel engines having a major dimension greater than 6 feet. A large propulsion diesel, gas turbine or main reduction gear might be good choices for representation using the rectangular surface source shown in Figure 1.[6]

In the context of sound field mapping, sound pressure level contour maps produced by simple point sources will produce circular contours of equal sound pressure level when mapped into a horizontal plane at ear level. Equal sound level contours computed using horizontal line sources will appear more elongated and elliptically shaped. As one would expect, a box-like surface source will generate contours that appear almost "box" shaped, having rounded corners at very short distances and becoming more elliptically shaped at greater distances.

Equipment Directivity Factor

Prediction accuracy in the direct field requires the selection of applicable equipment directivity factors. Both point and line equipment noise source models can be used with a suitable directivity factor (or Q_i) of: 1, 2, 4 or 8 to adjust for equipment location relative to compartment boundaries. When deck mounted to a single reflecting surface, Q_i=2, for equipment secured to a deck and near a single bulkhead, Q_i=4, and for items secured to a deck and near two bulkheads, assign Q_i=8. Note that the Q factor used is independent of the octave-band frequency and is treated as though strictly a consequence of local reflecting boundaries.

Room Constants

The room constants, which are necessary to estimate the contribution of multiple reflections to noise, or the reverberant field noise, must be computed accounting for the absorption coefficients of all compartment boundary surfaces and their possible insulation materials directly exposed to the air. A good number of representative candidate sound absorption coefficients for insulation materials can be found in Reference 1 and 2. Specific absorption coefficients for newer commercial insulation materials should be obtained from vendors and used cautiously unless the vendor has had tests performed at an independent test lab. The room constants must be assigned to the space for each octave band, so the *j* subscript in the variable name as in the *j*th octave. This must be done to account for the reflected sound field in each octave band. It will be necessary to compute the nine octave band values for Rc_j. These constants describe how absorptive a space is to acoustic power. The larger and more absorptive a space and the larger the percent of its boundary surface covered with a soft surface finishing material, the greater the value of the room constant.

Note that the equations to be introduced for the point, line and extended-surface sources must be evaluated for each equipment item (sources *i*=1 through *n*) and for each of the nine standard octave-band frequencies (*j*), starting at 31.5, 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. Then each of the nine octave-band levels must be A-corrected and logarithmically summed to produce the overall bottom-line single figure A-weighted sound level. A tabular format is usually employed by computer programs or in-hand calculations. To avoid possible confusion caused by subscripts, when reading through the following equations, think in terms of the *i*th equipment noise source in the *j*th octave band (*j*=1 to 9). The *j* subscript will be dropped after we introduce the A-weighted sound power level (PWL_a) and define the average A-weighted room constant (R_a), which will greatly simplify the work required.

Point-source model (for small items):

$$SPL_{i,j} = PWL_{i,j} + 10\log\left(\frac{Q_i}{4\pi r_i^2} + \frac{4}{R_{cj}}\right) + 10.5 \qquad (1)$$

where:

$SPL_{i,j}$ = sound pressure level (dB re 20 μPa) produced by the *i*th equipment point source in the *j*th octave

$PWL_{i,j}$ = *i*th point source sound power level in the *j*th octave in dB re 10^{-12} Watts

Q_i = *i*th point source directivity factor Q=1, 2, 4 or 8, depending on location

r_i = radial distance in feet between point source *i* and noise measuring location

R_{cj} = room constant for the space in *j*th octave band frequency (see below) and applicable to all three sources

$$R_{cj} = \frac{a_{j\text{ ave}}}{1 - a_{j\text{ ave}}} A\text{ boundary total} \qquad (2)$$

$$a_{\text{ave}} = \frac{A_1 a_1 + A_2 a_2 + \ldots + A_n a_n}{A_1 + A_2 + \ldots + A_n} \qquad (3)$$

$$R_{Sj} = \text{material}_1 A_1 + \text{material}_2 A_2 + \ldots + \text{material}_n A_n \qquad (4)$$

Line source model (cylindrical radiation and corrections for hemispherical end caps):

$$SPL_{i,j} = PWL_{i,j} + 10\log\left(\frac{Q_i}{4\pi 4_{si}^2 + 2\pi r_{ci} L_i} + \frac{4}{R_{cj}}\right) + 10.5 \qquad (5)$$

where:

L_i = length of *i*th line source in feet

A_{ci} = $2\pi r_c L$ and $As_i = 4\pi r_{S\,i}^2$ are cylindrical and spherical portions of the radiation surface area in ft^2

R_{cj} = room constant for space in *j*th octave band frequency

Rectangular Surface Model (rectangular length *L* width *W* and Height *H*):

$$SPL\ D_{i,j} = PWL_{i,j} - 10\log \left[(W_i L_i) + 2(W_i H_i + L_i H_i) + \pi r_i (W_i + L_i) + 2\pi r_i H_i + 2\pi r_i^2\right] + 10.5 \qquad (6)$$

$$SPL\ R_{i,j} = PWL_{i,j} + 10\log\frac{4}{Rc_j} + 10.5 \qquad (7)$$

this equation is always true for all sources

where:

$SPL\ D_{i,j}$ = direct sound pressure level produced by *i*th surface source in *j*th octave

$SPL\ R_{i,j}$ = reverberant sound pressure level produced by *i*th surface source in *j*th octave

$PWL_{i,j}$ = extended rectangular source *i* sound power level in *j*th octave, dB re: 10^{-12} watts

r_i = shortest perpendicular distance in feet between surface source *i* and noise measuring location

L_i = length of rectangular source in ft

W_i = width of rectangular source in ft

H_i = height of rectangular source in ft

HVAC Duct Breakout Noise

Duct breakout noise is produced by the acoustic power transmitted or "breaking out" of the source duct in question and into the space through the duct wall and can be calculated using this equation:

$$PWL_{i,j}\text{ external} = PWL_{i,j}\text{ internal} - TL_j + 10\log\frac{P_i L_i}{A_{i\text{ flow}}} \qquad (8)$$

Required for this calculation are the duct wall transmission losses (*TLj*) in each of the nine octave bands and the ratio of exterior radiation surface area to the duct cross-sectional flow area. The exterior radiation surface area of the duct is simply the perimeter of the duct (*P*) in feet times the length (*L*) of exposed duct in feet, and the flow area (A Flow) results in the grouping *PL*/[A Flow] illustrated above. After the external sound power levels have been calculated for the duct (in dB re 10^{-12} watts), the point or line source model may be selected based on its size and shape.

Transmitted Adjacent Space Noise Models

Noise transmitted from an adjacent noisy space is calculated using the equation below. The term $SPL_{R\,i,j}$ is the transmitted sound pressure level on the receiver side of the common area and must be log-summed with directly radiated noise in the space. $SPL_{S\,i,j}$ is the sound pressure level in the adjacent noisy source space, TL_j is the transmission loss of the common boundary in the octave being considered, and Rc_j is the room constant in the receiver space in the octave band under consideration.

$$SPL_{R\,i,j} = SPL_{S\,i,j} - TL_j + 10\log\left(\frac{Ac_i}{Rc_j} + 0.25\right) \qquad (9)$$

where:

$SPL_{R\,i,j}$ = transmitted noise on receiver (quiet) side of common boundary

$SPL_{S\,i,j}$ = sound pressure level on source side of common partition

TL_j = frequency-dependant transmission loss in *j*th octave band

A_{ci} (ft^2) = common (bulkhead, deck or overhead) area having TL_j

R_{cj} (ft^2) = room constant in *j*th octave band in question (see above)

The noise transmitted through the common bulkhead persists in the receiver space for a distance of perhaps the single width of the common boundary. This level is usually modeled like an all-pervasive reverberant noise level. According to Leo L. Beranek,[7] however, after that distance, the transmitted noise continues to slowly drop off with additional accumulated distance to a residual transmitted sound pressure level, $SPL_{R\,i,j}$'. (Note that the 0.25 term is simply dropped.)

$$SPL_{R\,i,j}' = SPL_{S\,i,j} - TL_j + 10\log\frac{Ac_i}{Rc_j} \quad \text{SPL}_{R\,i,j}' < SPL_{R\,i,j} \qquad (10)$$

where $SPL_{R\,i,j}$' is the residual transmitted noise in the receiver space persisting beyond some distance from the wall greater than the common bulkhead width. Since the residual noise level $SPL_{R\,i,j}$' is less than the transmitted noise level near the common bulkhead, most practitioners assume that $SPL_{R\,i,j}$ is the transmitted noise level throughout the receiver space. This assumption is safer and usually valid or conservative, except in the case of an extremely narrow common bulkhead and a very large receiver space. This fine detail is not usually modeled, although it can be with some form of curve-fitting technique that reproduces both $SPL_{R\,i,j}$ and $SPL_{R\,i,j}$' at suitable locations to answer potential inquiries from responsible program managers.

Sound Field Mapping

Since I am not a professional programmer, the following information is offered as advice from one engineer to another. The best way to create a noise contour map depends on the computer language you are working in. When FORTRAN, BASIC and COBOL were the only codes available, subscripting was used. On occasion I have used the subscript k to represent a specific noise-measuring location so that the working equations are subscripted as follows:

$$SPL_{i,j,k} = PWL_{i,j} + 10\log\left(\frac{Q_i}{4\pi r_{i,k}^2} + \frac{4}{R_{cj}}\right) + 10.5 \qquad (11)$$

This equation may be read as the contribution to the sound pressure level due to the ith noise source in the jth octave band and located at the kth noise-measuring location. Then by suitable summation of the subscripted variable, the total sound pressure level of all noise sources in the space can be determined at each frequency and at each location within the space. Individual sound pressure level contour maps can be plotted for each of the nine octave bands, and a single A-weighted sound level contour map can be produced by further processing the A-corrections and log or power summing the values of each of the nine maps. With Excel and other much more powerful graphics packages available, the optimum choice is wide open.

One practical tip – when mapping noise avoid evaluating sound levels at distances closer than three feet from point source models, as predictions at shorter distances may become unrealistically high, similar to a singularity. This can be handled using a clipper on values of the radius, limiting the standoff to not less than three feet.

If the data are to be plotted to the screen and color coded to represent sound level with no further processing, a small increment in model space is suggested of perhaps 0.1 to 0.5 feet along the deck. If some post-processing tool is to be applied to interpolate the predicted sound levels between predictions, a larger distance of 1 or even 5 feet will do between evaluation points. This can significantly reduce computation and storage requirements. I suggest that the raw computed data be named and filed for future use and possible re-plotting in different graphical styles.

A plan view is required for sound level contour maps, and I suggest color coding the highest noise level pixels in red and decreasingly lower sound level values as orange, yellow, green, blue and violet, for example. Scales of between one and two decibels per contour are recommended. Fortunately, the dynamic range is usually not so great between the maximum and minimum values of sound level in a space to warrant many different and hard to discriminate colors. If each pixel will be color coded there will be no problem identifying borders between adjacent contours. If no color code is to be used, some form of topographical mapping program will be required to create curved contours of sound level, as is done in land surveying.

One suggested version of free mapping software produces an isometric projection of the contour map by adding elevation to color for rapid eye recognition of levels. This can be done with the powerful Gnuplot[8] as shown in Figure 2. All of these features have been incorporated in a general purpose sound level and mapping (SLAM) code. In addition, there are supplementary views of the sound field from a forward vantage point looking aft and a starboard vantage point looking to port. These supplementary views are easy to generate by plotting sound level versus position in feet forward of the aft bulkhead for lines of constant distance from the ship center line, as illustrated in Figure 3.

Figure 4 illustrates sound level in dBA versus the transverse location for lines of constant longitudinal coordinate. Figure 5 illustrates the desired sound level contours predicted for a main machinery room containing two main propulsion diesel engines and two propulsion reduction gears.

Single Equivalent A-Weighted Room Constant

The following material is presented with some trepidation, knowing the cautions of George Diehl (Ingersoll Rand), who reminds us from the backwaters of Reference 9 not to rely too heavily on the A-weighted decibel scale. Notwithstanding, the test findings indicate that this tool is sufficiently accurate to map the A-weighted sound level, where a number of similar or identical equipment dominates the noise in a shipboard machinery space.

The notion that a useful, single, equivalent A-weighted room constant might exist occurred to me once I recognized that if one started with the calculated A-weighted value of sound power level (PWL_a), it was a short analytical trip to the correct A-weighted sound pressure level. This problem was not solved using physical theory but only intuition. It was also encouraging when I noticed that industrial standards appeared on the scene to define the now-standard A-weighted sound power level. The effective room constant was estimated after first backing out the numerical value that would produce the correct A-weighted sound level and noting it to have a magnitude approximately equal to some weighted average room constant. This appeared especially true if the most important octaves containing the greatest remaining acoustic power after application of the A-corrections were considered with the greatest weighting in the algorithm.

A series of a five candidates presented themselves as reasonable for an A-weighted average and were tested. Three were very simple to use; two were more complex, but they all produced close results,

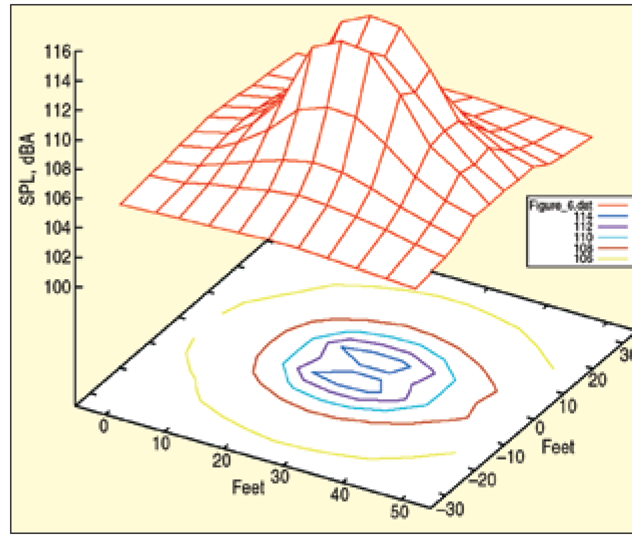

Figure 2. A-weighted sound level contours possible with GNUPLOT plotting code.

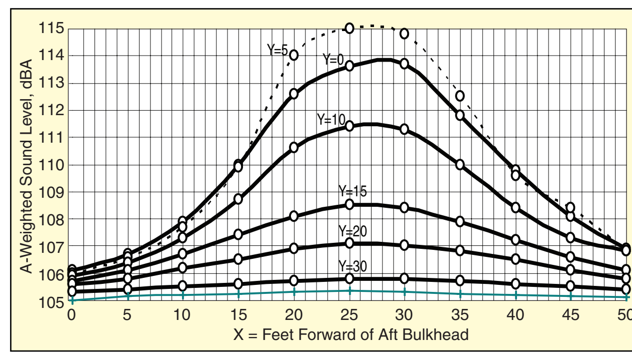

Figure 3. Sound level in dBA vs. longitudinal position for lines of transverse position.

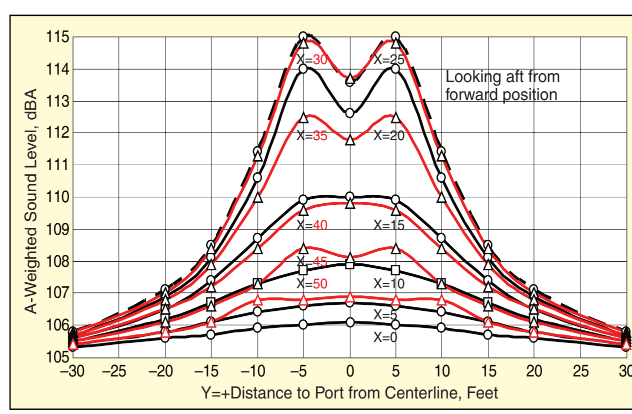

Figure 4. Sound level in dBA vs. transverse location for lines of constant longitudinal coordinate.

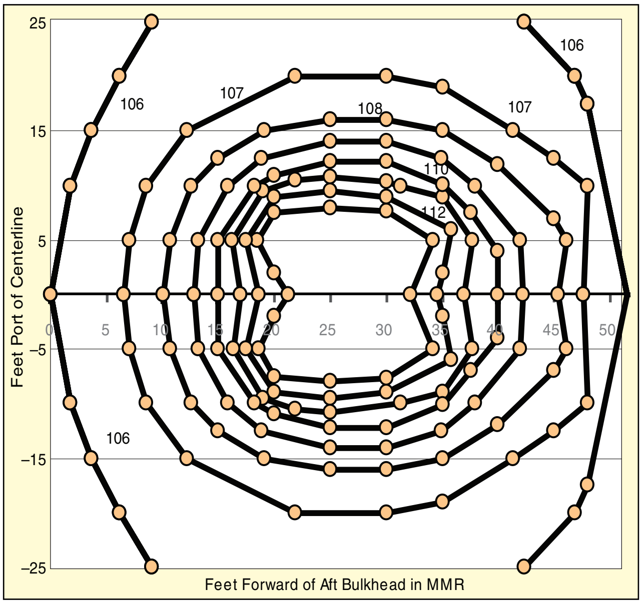

Figure 5. A-weighted sound levels predicted for main machinery room diesels.

usually within 0.5 dB and occasionally within 1.5 dBA of the correct answer. Noticing that a sixth new added form always obtained the precise answer for the reverberant field for every test case in a very large sample size and within 0.1 dBA, we concluded that the problem was solved. This favorable result has continued over the years, as this quick approximation was added to my codes that automatically cross-checked my rapid solution against the value of the full solution with good agreement.

If provided, the nine individual octave-band sound power levels appearing below for a main propulsion diesel engine or similar piece of equipment, we may compute the corresponding A-corrected octave-band sound power levels for the equipment by a simple sum in each octave with the A-corrections. The nine standard octave-band corrections applicable to both sound pressure levels and sound power levels are: –39.4, –26.2, –16.1, –8.6, –3.2, 0.0, 1.2, 1.0, and –1.1 dB. We then log-sum or power-sum the nine resulting A-corrected octave-band sound power levels to obtain the 123.5 dBA overall A-weighted sound power level (PWL_a) for the diesel. This is a standard transaction often performed and is described in several noise references and standards[10,11] and illustrated in Table 1.

Next, we examine a complete set of nine typical octave band room constants obtained by the methods described in the preceding sections for a main machinery room aboard a ship. Within this space, the A-weighted power spectrum of the diesel engine, which dominates the noise in the space, is used to help define a single equivalent A-weighted room constant (R_a) using the method illustrated in Table 2. W_{ai} is the raw acoustic power in watts remaining in each octave band after A-corrections.

$$SPL_i \text{ reverb} = PWL_a + 10\log\frac{4}{R_a} + 10.5 = \tag{12}$$

$$123.5\text{ dBA } + 10\log\frac{4}{7470} + 10.5 = 123.5 - 22.2 = 101.3\text{ dBA}$$

Adding the numbers in the bottom two rows containing numbers in scientific notation we obtain 2.23×10^{12} and 2.98×10^{8}, respectively. Dividing the larger by the smaller we obtain 7470 as the A-weighted room constant R_a.

$$\text{average room constant }(R_a) = \frac{\Sigma \dfrac{1}{R_{cj}}\dfrac{W_{a\,i}}{W_0}}{\Sigma \dfrac{W_{a\,i}}{W_0}} \tag{13}$$

Since we know from Table 1 that the equipment A-weighted sound power level is 123.5 dBA re 10^{-12} Watts, as well as the newly defined A-weighted average room constant (of R_a=7470 ft^2), it is now possible to compute the reverberant, direct and total A-weighted sound pressure level. This can be accomplished *without* first calculating each individual octave-band sound pressure level, A-correcting the bands, and then log-summing them. We write the relationship for the reverberant field which is sensitive to the room constant, and noting that all *j* subscripts have been dropped, since we are not working in any single octave but are using A-weighted decibels that address all weighted octaves simultaneously.

$$\text{A-weighted average room constant} = R_a = \frac{2.23\times10^{12}}{2.98\times10^{8}} = 7470 \tag{14}$$

The direct-field sound pressure level can also be calculated by using the standard A-weighted sound power level PWL_a of 123.5 dBA and our standard working equation for the correct point or line source; the total can be found by log addition.

Or one may simply find the A-weighted sound level for each source in the semi-reverberant field using the appropriate source equation and by working with the standard A-weighted sound power level PWL_a, and the A-weighted average room constant R_a.

Suggestions for Future Research

When attempting to duplicate actual airborne noise test data with SLAM prediction codes, it is often possible to obtain a fairly precise match with the actual noise test data with some minor adjustment to standard inputs. Occasionally, the measurements may contain some error, but one would hope that prior calibration efforts would minimize this. When trying to measure very low noise levels in a quiet stateroom or pilot house, even a misplaced whisper can cause a problem, while more consistently high noise levels can be recorded in machinery spaces without interference. Naturally, when the adjustment required for agreement with noise test data appears in an unlikely direction or to be unreasonably large, the thought is dropped. Such cases included improved transmission losses exceeding more than two standard deviations of historic transmission loss test data or severely degraded transmission losses due to an unanticipated flanking path.

A successful methodology might be one that runs an automated and directed search for input parameters requiring adjustment to

Table 1. Conversion of equipment octave-band sound power levels to single A-weighted sound power level (123.5 dBA re 1×10^{-12} watts overall).

	Octave-Band Number								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Octave-Band Frequency, Hz	31.5	63	125	250	500	1000	2000	4000	8000
PWL PDE True	103.5	105.5	111.5	111.5	111.5	111.5	110.5	121.5	109.5
A-Corrections, dB	–39.4	–26.2	–16.1	–8.6	–3.2	0.0	1.2	1.0	–1.1
PWL_{ai} A-Corrected	64.1	79.3	95.4	102.9	108.3	111.5	111.7	122.5	108.4

Table 2. Calculation of single equipment A-weighted room constant.

	Octave-Band Frequency, Hz								
	31.5	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Standard Room R_{ci}	654	392	774	5031	6283	8699	7664	7664	6167
PWL_{ai} PDE	64.1	79.3	95.4	102.9	108.3	111.5	111.7	122.5	108.4
W_{ai}/W_0 A-Weighted	2.57×10^{6}	8.51×10^{7}	3.47×10^{9}	1.95×10^{10}	6.76×10^{10}	1.41×10^{11}	1.48×10^{11}	1.78×10^{12}	6.92×10^{10}
$(1/R_{ci})\times(W_{ai}/W_o)$	3.93×10^{3}	2.17×10^{5}	4.48×10^{6}	3.88×10^{6}	1.08×10^{7}	1.62×10^{7}	1.93×10^{7}	2.32×10^{8}	1.12×10^{7}

reduce (prediction versus measurement) residuals. These could either be changes in the assumed math model or material acoustic performance data such as transmission loss or sound absorption coefficient. Since it is also possible that *some* measurement error may be present in sound level test data, this must also be considered in the formulation. How often have two independent survey teams produced data demonstrating a number of decibels of disparity exceeding their instruments tolerance bands for noise recorded in the same space for supposedly identical conditions? Where test conditions, including ships speed, heading, power settings and equipment lineups have been held as fixed as is humanly possible, this is indeed disappointing.

It was in a fit of frustration with some recent test data that I remembered the work I participated in back in the late '70s and early '80s at United Technologies in a joint effort between Pratt & Whitney Aircraft (P&WA) and Hamilton Standard (HS) called Gas Path Analysis (GPA). GPA was named and conceived of by Louis A. Urban of Hamilton Standard incorporating a probabilistic Kalman digital filter.[12] Product support engineering at P&WA was having a good measure of success in diagnosing gas turbine engine module faults deterministically for the JT9D engine using a method called vector analysis, and our codes were strictly based on thermodynamic influence coefficients. P&WA discussed what could be done to improve our successful hit rate, which was measured to be somewhat greater than three out of four engines and up to perhaps 80%.

We formalized these methods into what was called the Module Analysis Program (MAP) and used it to assist us in the selected maintenance actions on operator engines. As we later learned, the probabilistic approach was somewhat more successful at identifying the faulty engine module with improved average hit rates. Based on teardown and inspection findings, we increased our successful hit rates from 75 to perhaps 85 or even 90% using the probabilistic GPA approach of Urban and Volponi.[13] However, the most reliable assessment of the underperforming engine module also required determining the most probable error in test instrumentation; these measurements required some form of filtering. We went on to develop several Kalman digital filters that proved useful in improving the diagnostic hit-rate. We believed this to be most effective for our airborne integrated data system (AIDS) for in-flight recording of data.

It is suggested that a similar approach be attempted when trying to obtain agreement between noise predictions and measurements. Indeed this may have been quietly done already by certain competing organizations engaged in noise testing. In any case, the idea appears worthy of some follow-up by the noise community. The form the method might take could range from simply minimizing the sum of the square of errors to a full Kalman digital filter or some other recent or perhaps more promising approach from digital filtering.

Conclusions

Much work remains in the important field of shipboard airborne noise control, and new papers, texts, and special-purpose programs are being written every day. Considered noteworthy is Reference 14, which outlines the origins of shipboard noise limits, ship specifications, acoustic control plans, special-purpose noise source models and formulations. It also provides valuable data on equipment noise source levels, material absorption coefficients, and transmission losses, as well as information on structure-borne noise contributions to the airborne noise problem. This valuable reference is similar in scope to the original SNAME T&R 3-37.[1,2]

In addition, several promising new programs have been written that employ finite-element analysis, boundary-element analysis, and statistical-energy analysis techniques to predict airborne noise from structure-borne noise and other ship sources. These models can be used to assemble partial or dedicated full ship noise models and are considered very powerful new tools important to the future of ship noise control.

Acknowledgement

I would like to thank James T. Higney, a former president and chief engineer of Gibbs & Cox, Inc. for his encouragement on this paper and for reviewing and commenting on the final draft. I also want to thank my long-time friend and coworker at G&C, Buck Godwin, for his many suggestions and for providing assistance in the use of Gnuplot.

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