Innovative Approach for Developing Spacecraft Interior Acoustic Requirement Allocation

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ABSTRACT

The Orion Multi-Purpose Crew Vehicle (MPCV) is an American spacecraft for carrying four astronauts during deep space missions. This paper describes an innovative application of Power Injection Method (PIM) for allocating Orion cabin continuous noise Sound Pressure Level (SPL) limits to the sound power level (PWL) limits of major noise sources in the Environmental Control and Life Support System (ECLSS) during all mission phases. PIM is simulated using both Statistical Energy Analysis (SEA) and Hybrid Statistical Energy Analysis-Finite Element (SEA-FE) models of the Orion MPCV to obtain the transfer matrix from the PWL of the noise sources to the acoustic energies of the receivers, i.e., the cavities associated with the cabin habitable volume. The goal of the allocation strategy is to control the total energy of cabin habitable volume for maintaining the required SPL limits. Simulations are used to demonstrate that applying the allocated PWLs to the noise sources in the models indeed reproduces the SPL limits in the habitable volume. The effects of Noise Control Treatment (NCT) on allocated noise source PWLs are investigated. The measurement of source PWLs of involved fan and pump development units are also discussed as it is related to some case-specific details of the allocation strategy discussed here.

NOMENCLATURE

ANCL	Acoustics and Noise Control Laboratory
ARS	Air Revitalization System
CLF	Coupling Loss Factor
CSM	Crew/Service Module
CPP1	Coolant Pump Package 1
CM	Crew Module
DLF	Damping Loss Factor
DOF	Degree of Freedom
ECLSS	Environmental Control and Life Support System
EFT-1	Exploration Flight Test 1
EM-2	Exploration Mission 2
FE	Finite Element

HSIR	Human-Systems Integration Requirements
JSC	NASA Johnson Space Center
KSC	NASA Kennedy Space Center
MAJ	Manual Area Junction
MHAJ	Manual Hybrid Area Junction
MPCV	Multi-Purpose Crew Vehicle
NCT	Noise Control Treatment
PIM	Power Injection Method
PV	Pressure Vessel
PWL	Sound Power Level
SEA	Statistical Energy Analysis
SIF	Semi-infinite Fluid
SPL	Sound Pressure Level
c	Speed of sound
L_{pi}	SPL of cavity i
L_{wi}	Input PWL into cavity i
$L_{w_i}^{nom}$	Input PWL, at nominal operating point, into cavity i
p_{ref}	Reference sound pressure ($20 \mu Pa$)
V_i	Volume of cavity i
P_i	Input sound power at cavity i
P_i^{nom}	Input sound power, at nominal operating point, into cavity i
ρ	Density of air
ω	Radian frequency

1 INTRODUCTION

A high-noise environment may increase the risk to safety, health and productivity of the crew due to fatigue, reduced communication effectiveness, and increased risk of temporary and permanent hearing loss, particularly for long duration spaceflight. Therefore, Orion cabin continuous noise SPLs are subjected to limits specified in the HSIR. Since major noise sources in the Orion CM are located in ECLSS, the contribution of ECLSS to cabin continuous noise SPL is limited by NC-50. NC-50 is an integrated vehicle level requirement, while there are several noise sources in ECLSS, such as cabin fans, ARS fans, and CPP1. It is necessary for these fans and pumps to be developed in parallel with the Orion vehicle and to meet NC-50 during the integrated vehicle level test. In order to accomplish this, the NC-50 requirement needs to be divided into allocations for each noise source. Furthermore, the emitted SPL of a hardware item (i.e. noise source) is dependent on the environment where the hardware is tested/evaluated, whereas the PWL of a hardware item is only dependent on the noise emitted from the source itself and is independent of the test environment. Therefore, for verification of stand-alone hardware end items, allocated requirements in the PWL metric are appropriate. PWL is also the information needed as inputs to the SEA-FE models.

   This paper describes an innovative approach for allocating system-level SPL limits to hardware end item/component level PWL limits. The approach is based on the PIM, which has been used widely to obtain experimentally validated SEA models[1,2]. PIM is used to obtain the transfer matrix from the PWLs of the noise sources to the acoustic energies of the receivers, i.e., the cavities associated with cabin habitable volume. Without a physical Orion MPCV fully equipped with ECLSS hardware, PIM is instead simulated, using SEA and Hybrid SEA-FE models to represent the Orion MPCV. The Hybrid model has a higher fidelity representation of the ECLSS. The allocation approach is to control the total acoustic energy in the cabin habitable volume to

maintain the required limit of NC-50. Simulations are used to verify that applying the allocated source PWLs to these models indeed reproduces NC-50 in the habitable volume.

The effects of NCT on the allocated noise source PWLs are investigated. The sound power measurement of involved fan and pump development units is also discussed with the details on deriving the source PWL from measured PWL.

2 METHODOLOGY

The PIM starts with the power balance equation, which has the form

$$\mathbf{L} \begin{Bmatrix} E_1 \\ \vdots \\ E_N \end{Bmatrix} = \frac{1}{\omega} \begin{Bmatrix} P_1 \\ \vdots \\ P_N \end{Bmatrix} \tag{1}$$

where E_i is the averaged energy of DOF i (i.e., subsystem i) and P_i is the power input to DOF i. For duct-borne inlet/outlet noise associated with a fan, P_i refers to the sound power of the source, free from the effects of ductwork. For input into SEA and Hybrid SEA-FE models, P_i is the power source to a SEA acoustic cavity or the monopole source to an FE acoustic cavity. Source sound power is different from measured inlet/outlet sound powers and will be discussed in details in a later section. Matrix $\mathbf{L}$ contains the CLFs and DLFs. Equation (1) is then transformed into the following form to be useful for PIM.

$$\mathbf{E^n} \begin{Bmatrix} P_1 \\ \vdots \\ P_N \end{Bmatrix} = \begin{Bmatrix} E_1 \\ \vdots \\ E_N \end{Bmatrix} \tag{2}$$

where $\mathbf{E^n}$ is the normalized PIM energy matrix with its element E_{ij}^n representing the energy of subsystem i (DOF i) due to unit power input into subsystem j (DOF j). Orion MPCV system model has hundreds of DOFs, which are divided into 3 sets.

- a-set contains the source cavities: Input 1, ARS fan 1 cavity; Input 2, ARS fan 2 cavity; Input 3, Cabin fan 1 cavity; Input 4, ECLSS bay cavity +Y (both CPP1 1A/2A and 1B/2B pumps reside in this cavity).
- b-set contains the receiver cavities: Receiver 5, Cabin habitable volume cavity +Y, and Receiver 6, Cabin habitable volume cavity -Y. DOFs 5 and 6 will be merged into a single DOF as this will be discussed later.
- c-set contains the remaining cavities, plates, shells, and beams.

Equation (2) can then be rewritten in terms of the above 3 sets of DOFs.

$$\begin{bmatrix} E_{aa}^n & E_{ab}^n & E_{ac}^n \\ E_{ba}^n & E_{bb}^n & E_{bc}^n \\ E_{ca}^n & E_{cb}^n & E_{cc}^n \end{bmatrix} \begin{Bmatrix} P_a \\ P_b \\ P_c \end{Bmatrix} = \begin{Bmatrix} E_a \\ E_b \\ E_c \end{Bmatrix} \tag{3}$$

As we are concerned only with the inputs from the sources in the a-set, hence $\mathbf{P_c} = 0$. Also, we do not care about the responses of the c-set. Therefore, the last row in the above equation can be neglected. In fact, we only care about the responses of the b-set, i.e., the middle row. Furthermore, there are no direct power inputs into the receiver cavities although it can be dealt with slight modification in the formulation. With $\mathbf{P_b}$ set to 0, we have the following

$$\mathbf{E_b} = \mathbf{E_{ba}^n P_a} \tag{4}$$

For multiple connected receiver cavities, the intention here is to control the total energy, not the individual energy, of these cavities to reach the target SPL. Orion MPCV system model has

two receiver cavities: cabin habitable volume cavity +Y as DOF 5, and cabin habitable volume cavity -Y as DOF 6. DOFs 5 and 6 are merged into a single DOF b so that the SPL of DOF b is the volume weighted average SPL of DOFs 5 and 6 as illustrated in the following:

$$E_i = \frac{V_i}{\rho c^2} p_{ref}^2 10^{L_{pi}/10} \quad i = 5,6,b \tag{5}$$

With $E_b = E_5 + E_6$ and $V_b = V_5 + V_6$, the following can be derived:

$$\frac{\langle p_b^2 \rangle}{p_{ref}^2} = \frac{V_5}{V_b} \frac{\langle p_5^2 \rangle}{p_{ref}^2} + \frac{V_6}{V_b} \frac{\langle p_6^2 \rangle}{p_{ref}^2}, \tag{6a}$$

$$L_{p_b} = 10 log_{10} \left(\frac{V_5}{V_b} 10^{L_{p5}/10} + \frac{V_6}{V_b} 10^{L_{p6}/10} \right). \tag{6b}$$

Expanding Equation (4) with respect to the four inputs gives the following:

$$E_b = E_{b1}^n P_1 + E_{b2}^n P_2 + E_{b3}^n P_3 + E_{b4}^n P_4 \tag{7}$$

Since the SPL in V_b is contributed to by the power inputs P_1, P_2, P_3, and P_4, it is more illustrative to split E_b into four parts with each part being contributed to by one of the power inputs. That is,

$$E_b = (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4)E_b \tag{8}$$

Here, we have $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$. Combining Equations (7) and (8) yields

$$(\alpha_1 E_b - E_{b1}^n P_1) + (\alpha_2 E_b - E_{b2}^n P_2) + (\alpha_3 E_b - E_{b3}^n P_3) + (\alpha_4 E_b - E_{b4}^n P_4) = 0 \tag{9}$$

For satisfying Eq. (9), it is sufficient to set

$$P_i = \alpha_i E_b / E_{bi}^n, i = 1,2,3,4 \tag{10}$$

Where $E_b = \frac{V_b}{\rho c^2} p_{ref}^2 10^{(NC-50)/10}$. α_i can be set depending on the ratio E_b/E_{bi}^n. E_{bi}^n can be obtained by injecting 120 dB flat-spectrum sound power to the model at the input DOF i and calculating the resulting energies of DOFs 5 and 6, i.e., E_{5i} and E_{6i}. The normalized energy E_{bi}^n can be calculated by $(E_{5i} + E_{6i})/P_i$. $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$ can be set at a value less than 1 so that the allocation can have some reserve left; however, it cannot be set to a value greater than 1 as the resulting allocation will cause the SPL of the habitable volume to exceed the NC-50 target.

2.1 Development of frequency-dependent allocations

Figure 1 shows the PWL comparison of ARS fan, cabin fan, and CPP1 pump package (with 2 pumps) for nominal operating points/conditions. The process of deriving these source PWLs from measured PWLs will be discussed in details in a later section. It is clear that the pump package is the least significant source in most of the frequency range. It was decided that the pump package will be allowed 3 dB of headroom above the PWL when the package is operated at the nominal operating point, namely, $P_4 = 2 \times P_{pumps}^{nom}$ and $\alpha_4 = P_4 \times E_{b4}^n/E_b$. Together with the constraint, $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$, the DOFs of $\alpha's$ are reduced to 2.

The remaining energy in the habitable volume, $(1 - \alpha_4)E_b$, is contributed to by P_1, P_2, and P_3. It is intended that the difference between the PWLs of the two ARS fans at the nominal operating point and corresponding allocated PWLs are equal to the PWL of the cabin fan at its nominal operating point and corresponding allocated PWL. The objective is to allow for a single muffler design for the ARS fans and cabin fan to comply with the allocated PWL requirements. These conditions generate two additional constraints and remove remaining DOFs of $\alpha's$ as described in the following.

The above constraints in fan PWLs is first written in log scale, i.e.,

$$L_{w_1}^{nom} - L_{w_1} = L_{w_3}^{nom} - L_{w_3} \tag{11a}$$

$$L_{w_2}^{nom} - L_{w_2} = L_{w_3}^{nom} - L_{w_3} \tag{11b}$$

Equations (11a) and (11b) can be rewritten in linear scale, i.e.,

$$\frac{P_1^{nom}}{P_3^{nom}} = \frac{P_1}{P_3} = \frac{\alpha_1}{\alpha_3} \frac{E_{b3}^n}{E_{b1}^n} \tag{12a}$$

$$\frac{P_2^{nom}}{P_3^{nom}} = \frac{P_2}{P_3} = \frac{\alpha_2}{\alpha_3} \frac{E_{b3}^n}{E_{b2}^n} \tag{12b}$$

Defining two new variables and rewriting Equations 12a and 12b yields

$$k_1 \equiv \frac{\alpha_1}{\alpha_3} = \frac{P_1^{nom}}{P_3^{nom}} \frac{E_{b1}^n}{E_{b3}^n} \tag{13a}$$

$$k_2 \equiv \frac{\alpha_2}{\alpha_3} = \frac{P_2^{nom}}{P_3^{nom}} \frac{E_{b2}^n}{E_{b3}^n} \tag{13b}$$

After k_1 and k_2 are calculated, $\alpha_1 = k_1 \alpha_3$ and $\alpha_2 = k_2 \alpha_3$ can be substituted into the constraint $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$ to calculate α_3 from α_4 as follows.

$$\alpha_3 = (1 - \alpha_4)/(1 + k_1 + k_2) \tag{14}$$

Then, α_1 and α_2 can be obtained after k_1, k_2, and α_3 are computed. With α_1, α_2, α_3, and α_4 being available, the allocated PWLs L_{w_1}, L_{w_2}, L_{w_3}, and L_{w_4} can be calculated.

As the PWL of only one ARS development unit was measured, $L_{w_1}^{nom}$ is equal to $L_{w_2}^{nom}$. Hence L_{w_1} is equal to L_{w_2} according to Eqs. 11a & 11b. Also, the allocation of L_{w_4} does not require the usage of the model, as it is set at 3 dB above the measured pump package PWL at each frequency band for its nominal operating point.
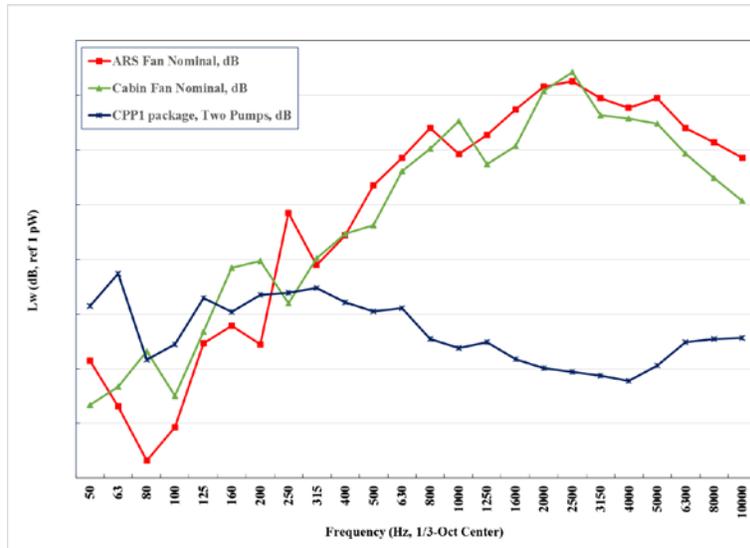

Figure 1: Source sound power comparison for hardware at nominal operating points

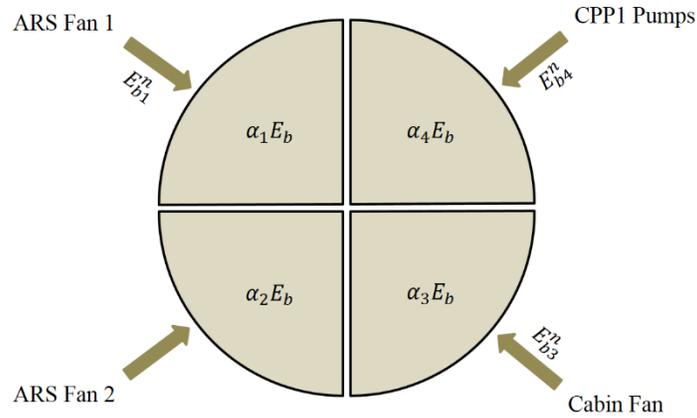Figure 2 shows an illustration of ECLSS source contributions to the cabin habitable volume total acoustic energy.

Figure 2: ECLSS source contributions to cabin habitable volume total energy

3 ECLSS NOISE SOURCE CHARACTERIZATION

The major ECLSS noise sources, i.e., ARS fan, cabin fan, and CPP1, have been characterized via SPL/ PWL measurements and post-measurement analysis to obtain noise source PWL free from the effects of test ductwork for this allocation development. Measured duct-borne noise PWL cannot be applied to the Orion system model directly due to the differences in ductwork between the ECLSS design and the test setup. This section describes how these differences are taken into account.

3.1 ARS fan sound power measurement and noise source characterization

Duct-borne inlet/outlet and case-radiated PWLs were measured from an ARS fan development unit in the anechoic chamber of JSC's ANCL. Figure 3 shows the setup for measuring duct-borne outlet sound power. Sound intensity scans were performed on 10 surfaces of a 1 m cube. The muffler was used to attenuate the inlet noise. Additional barrier treatments were used to reduce breakout noise from ducts and fan case-radiated noise. Inlet noise sound power was measured similarly with the inlet in the measurement cube and outlet noise being muffled. Case radiated sound power was measured with the fan case in the measurement cube and both inlet and outlet noise being muffled.
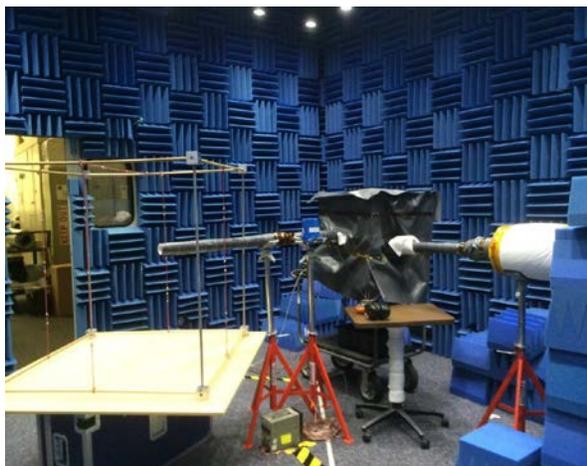

Figure 3: ARS outlet sound power measurement setup, photo and schematic

Both SEA and FE models of the test setup are used to remove the effects of the test ductwork on the measured PWLs and to obtain the source PWL. Figure 4 shows the SEA and FE models for

outlet noise test set-up. The fan noise source is modeled as a power source in SEA and as an acoustic monopole in FE. The purpose of using the FE model is that the fan and duct cavities in the SEA model lack enough modes-in-band for frequencies below 1,600 Hz and as a result, the SEA model tends to under-predict the duct-borne sound power, and hence overestimates the source sound power. Therefore, the SEA model is used for frequencies >1,600 Hz, while the FE model is used for frequencies ≤1,600 Hz. For deriving the source sound power from both models, measured outlet sound power is first used as the source sound power. It was found that case-radiated sound power is significantly lower than the duct-borne inlet/outlet sound powers and hence was not included in source characterization analysis. The average of the source sound powers from the outlet and inlet calculations was used as the source sound power of ARS fan, as shown in Figure 5.
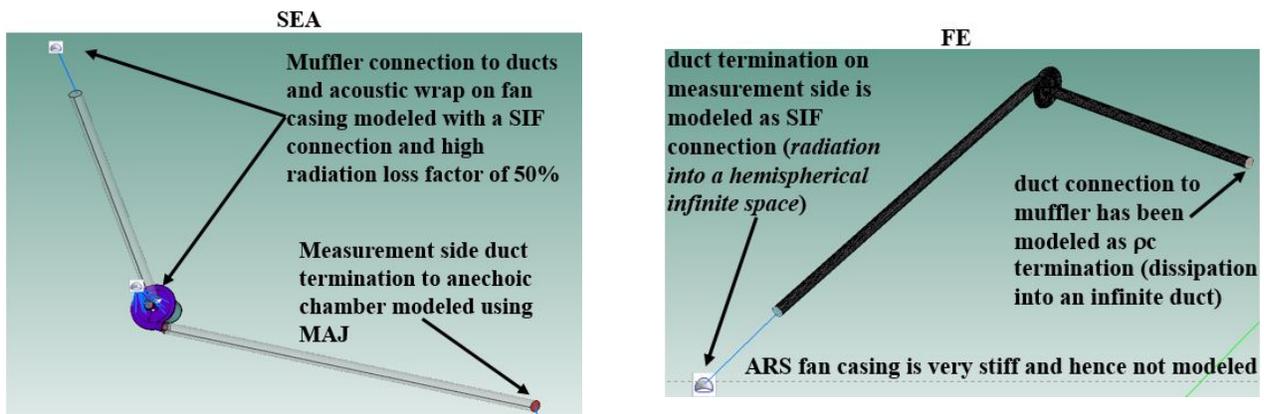
Figure 4: *SEA and FE model of ARS fan test setup for outlet noise measurement*
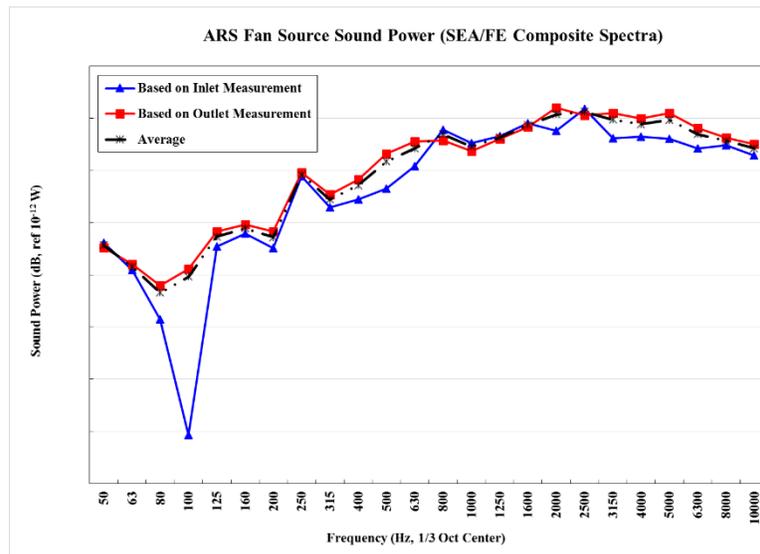
Figure 5: *ARS fan source sound power*

3.2 Cabin fan sound power measurement and noise source characterization

The process of sound power measurement and noise source characterization of the cabin fan follows that of the ARS fan. The only difference is that the inlet and outlet ducts of ARS fan are at right angles to each other as the ARS fan is a centrifugal fan; while the cabin fan ductwork is in a straight line as the cabin fan is an axial fan.

3.3 CPP1 sound power measurement and noise source characterization

Instead of a sound intensity scan, SPL measurements were made at different distances from the pump package during a CSM performance test of EFT-1 at the KSC Operations and Checkout facility. Background noise levels were high due to parallel testing and construction; however, audio recordings were made and sections of high extraneous noise were edited out prior to post-processing. The SPL calculation was corrected for background noise. Figure 6 shows the interior of EFT-1 and one of the measurement position with the pump package at the lower right corner. The pump package operated two pumps together during the test.

Figure 6: SPL measurement inside EFT-1

The source-receiver distance for the SPL measurements was: 1", 2', 4', and 5 ¾'. Assuming hemispherical radiation from the pump package, the Eyring equation is used to derive the source sound power.

$$L_p(r) = L_w + 10log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) \tag{14}$$

where
   r: source-to-receiver distance,
   Q: directivity factor = 2 for hemispherical radiation,
   R: room constant = $A/(1 - \alpha_d)$,
   A: total room absorption = $-Sln(1 - \alpha_d) + 4mV$,
   S: total PV interior surface area,
   V: PV interior volume,
   α_d: average diffuse field cabin surface absorption coefficient,
   $2m$: energy air absorption coefficient.

The only unknown in Equation (14) to derive L_w from L_p is α_d. It is found that spherical decay is not evident from measured SPLs, and hence the reverberant field was dominant. This is consistent with the fact that the interior of EFT-1 consists of hard surfaces. α_d should be very low and can be chosen from past experience or by minimizing the spread of L_w at the measurement locations for each frequency band. Figure 7 shows the α_d used in the estimation. Figure 8 shows the estimated source PWLs at SPL measurement locations. Only the first three estimates are averaged to obtain the sound power as the 1" distance measurement is probably in the near field of source and not suited for using the Eyring equation.
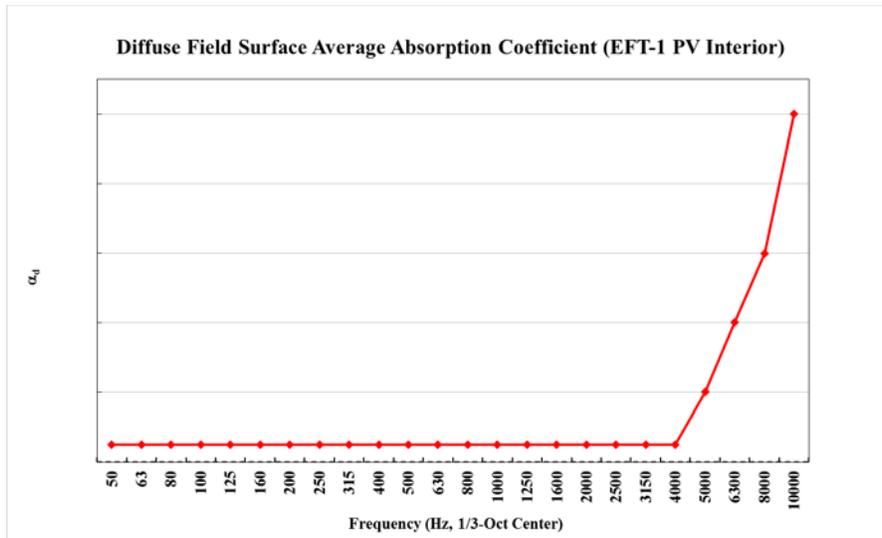
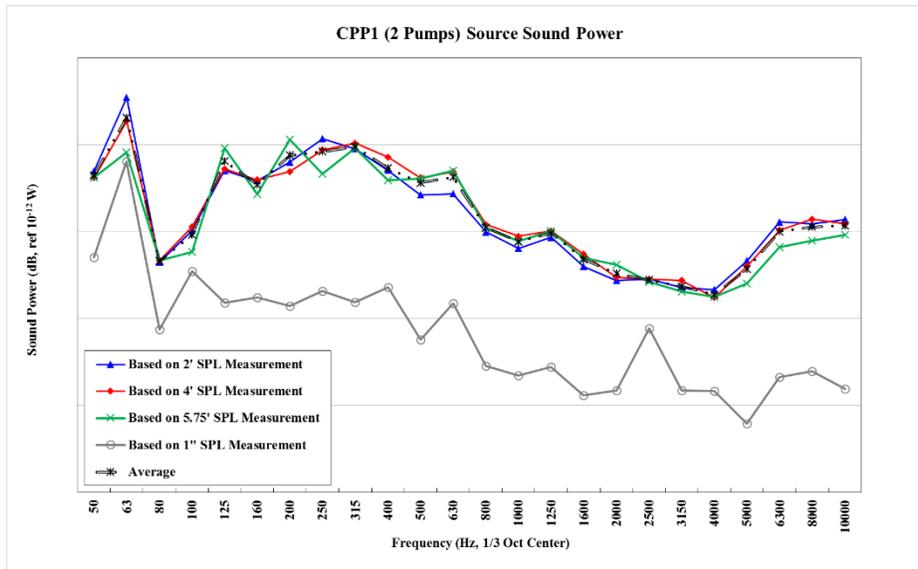**Figure 7:** *Diffuse Field surface average absorption coefficient of EFT-1 interior*

Figure 8: *Estimated source sound powers at SPL measurement locations*

4 ALLOCATION ANALYSIS RESULTS

Two types of Orion cabin system acoustic models are used for the PIM-based allocation analysis. A SEA-only model is used for frequencies above 1,600 Hz and a Hybrid SEA-FE model is used for frequencies up to 1,600 Hz. The hybrid model represents the entire ECLSS network (fluid and structure) , including noise sources and ductwork, in FE and the remaining cabin in SEA. The ECLSS network is connected to appropriate cabin and ECLSS bay SEA cavities via MAJs in the SEA model and MHAJs in the hybrid model. Figure 9 shows the two types of models.

Due to a lack of modes in low-to-mid frequency bands, ECLSS represented in SEA tends to under-predict the source-to-receiver gains from the ECLSS noise sources to the cabin as shown in Figure 10. The problem of under-predictions are more significant for the ARS fans and cabin fan, which have FE source cavities; while the problem is much less significant for CPP1, which has a SEA source cavity (ECLSS bay cavity +Y). Together with a fixed allocation for CPP1 at $2 \times P_{pumps}^{nom}$, regardless of the model used, the contribution to the cabin energy from the fans, i.e.,

$(1 - \alpha_4)E_b$, is virtually the same for both models. The net effect is that the SEA model will over-allocate the source PWLs for the fans. Figure 11 shows the allocated source PWLs for ARS fans 1 and 2, which are the same based on the formulation of the allocation scheme. Figures 10 and 11 also show the convergence of the two models near 1,600 Hz. The results for the cabin fan are found to be similar to Figures 10 and 11. Figure 12 shows that applying allocated source PWLs in the models indeed reproduces the NC-50 requirement as the volume weighted average SPL of the cabin habitable volume cavities. It is also verified by the simulation that Equations (11a) and (11b) are satisfied. Namely, the differences between allocated source PWL and measured source PWL at nominal conditions are equal for the ARS fans and cabin fan.
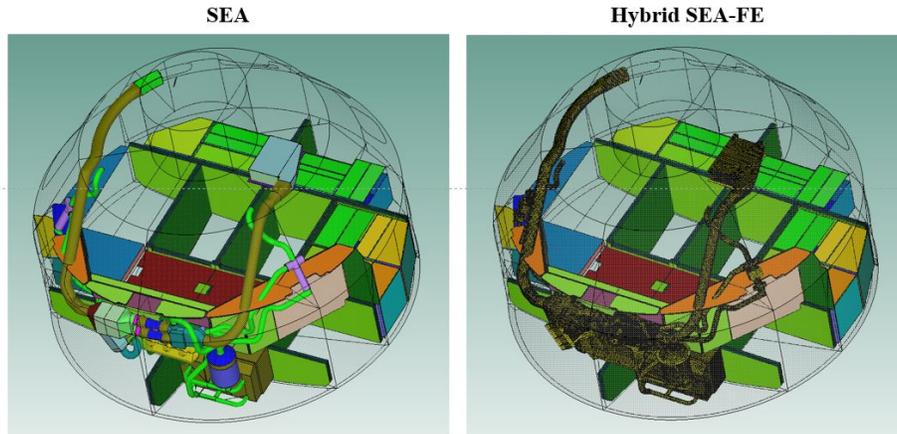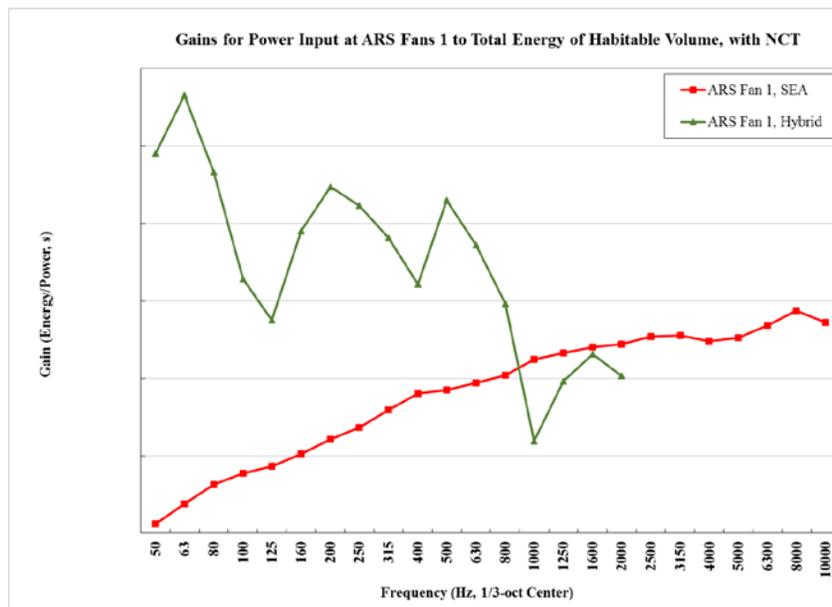

Figure 9: Orion cabin system models

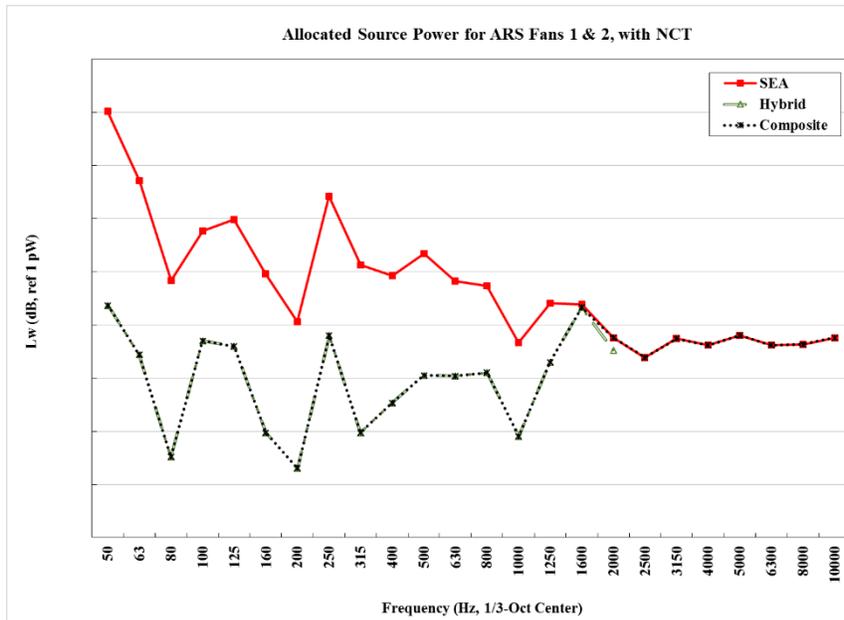*Figure 10: ARS fan 1 source-to-receiver gains, SEA vs. Hybrid SEA-FE*

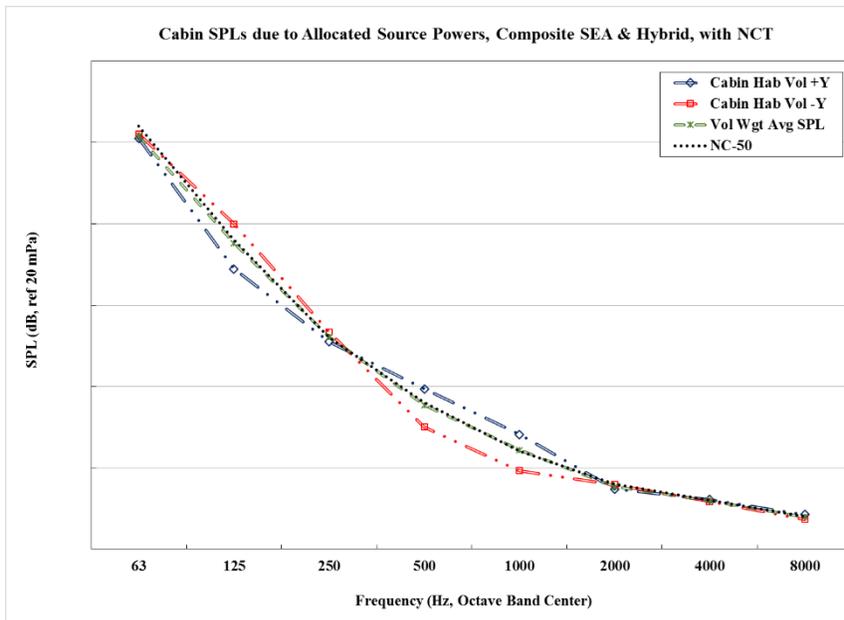**Figure 11:** *ARS fans 1&2 allocated source power, SEA vs. Hybrid SEA-FE*

Figure 12: *Cabin volume weighted average SPL due to allocated source powers*

The effects of applying NCT to the surfaces of cabin habitable volume on allocated source PWLs are investigated based on Equation (10). It is found that

- Source-to-receiver gains, i.e., E_{b1}^n, E_{b2}^n, E_{b3}^n, and E_{b4}^n, are reduced.
- With the CPP1 allocation set at $2P_{pumps}^{nom}$, α_4 decreases following the reduction of E_{b4}^n. Therefore, the total energy of the habitable volume that is contributed by the pump package is reduced. On the other hand, the contribution from the fans increases.
- The net effects on α_1, α_2, and α_3 are that α_3 increases while α_1 and α_2 remain about the same. Together with source-to-receiver gains, this allows for increased fan source power allocations in mid to high frequency bands as shown in Figures 13 and 14.

It can be seen from the above that there is a trade-off between applying NCT to cabin surfaces and making quieter ECLSS sources. The latter involves lined ECLSS ducts, mufflers, or quieter fans.
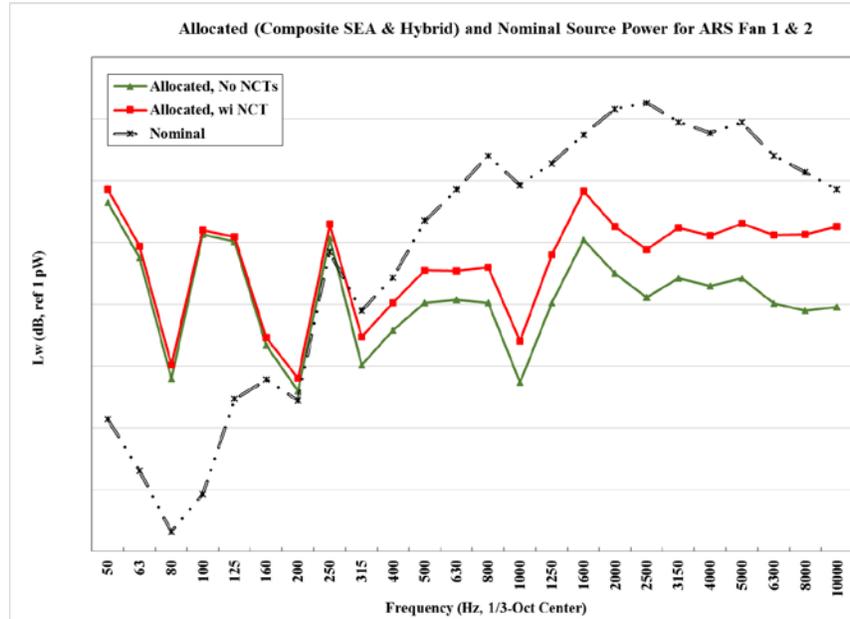

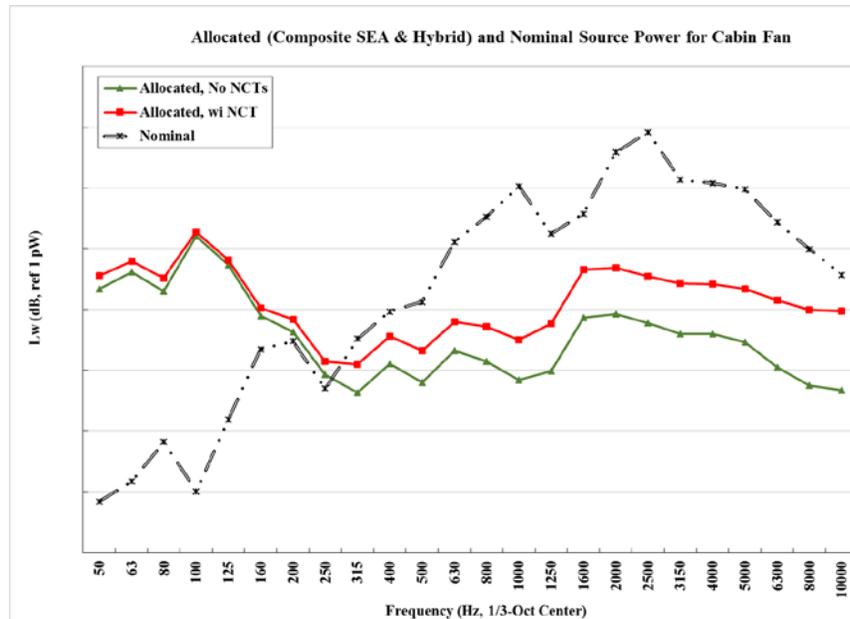**Figure 13:** *Allocated and nominal source powers for ARS fans 1&2*

Figure 14: *Allocated and nominal source powers for cabin fan*

5 CONCLUSION AND FUTHER WORK

A methodology for allocating the continuous noise SPL limits of the Orion crew cabin habitable volume to the PWL limits of major ECLSS noise sources was developed. The method is based on the PIM and controls the total acoustic energy in the Orion cabin habitable volume for maintaining the required limits at NC-50.

Four ECLSS noise sources were identified and included in the developed allocations: ARS fans 1 & 2, cabin fan, and CPP1 pump package. The inlet/outlet PWLs of the ARS fan and cabin fan development units at nominal operating conditions/points were measured; while SPLs at different distances from the CPP1 pump were measured inside the EFT-1 flight vehicle. Both SEA and FE models of fan test ductwork were used to derive source's PWLs, and the Eyring equation was used to derive the source PWLs of CPP1 from measured SPLs. The allocated level for CPP1 was set at 3 dB above the measured level at the nominal operating point, and the differences between the allocated source PWL and measured source PWL at the nominal operating point were set to be equal for ARS fans and cabin fan.

Both SEA and Hybrid SEA-FE were used for the allocation development. Representing ECLSS network using SEA instead of FE tends to under-predict the source-to-receiver gains and over-allocates the source powers for the fans.

The effect of applying NCT to cabin surfaces is that it can reduce source-to-receiver gains and hence allow for more lenient targets for noise sources in the mid-to-high frequencies. Therefore, there is trade-off between developing quieter sources and more effective NCT in the cabin.

The source PWLs derived here can be used to design ECLS component noise controls, such as mufflers and silencers. Since PIM is commonly used to obtain experimentally correlated models, the allocation strategy discussed here can be verified during the final Orion MPCV vehicle level acoustic tests.

ACKNOWLEDGEMENTS

REFERENCES

1. L. Hermans and M. ladevaia, "Guidelines on the use of Experimental SEA for modeling and understanding road noise in cars", *Proc. SEA Noise and Vibration Conf*, Traverse City, Michigan, US, (1999) pp. 431-442.
2. N. Lalor, "Practical Considerations for the Measurement of Internal and Coupling Loss Factors on Complex Structure", *ISVR Technical Report No. 182*, (1990).
3. R.H. Lyon and R.G. DeJong, *Theory and Application of Statistical Energy Analysis,* 2nd Edition, Butterworth-Heinemann, 1995.
4. D.A. Bies and C.H. Hansen, *Engineering Noise Control, Theory and Practice,* 2nd Edition, E & FN Spon, London & New York, 1996.