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Space Station Interior Noise Analysis Program

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1.0 INTRODUCTION

This report presents the mathematical algorithms used in the Space Station Interior Noise Analysis Program (SSINAP) to evaluate the effect of the vibroacoustic environment on speech communication inside a space station.

During normal operations, in an orbiting space station, operation of numerous mechanical systems will introduce noise and vibration into the contained environment.[1] A list of such noise and vibration sources will probably include, among other items: waste control systems; galley fans; personal hygiene stations; pressure regulators; reaction control system systems; data printers; fans, pumps, and motors of environmental control and life-support systems; and avionics. Post-flight debriefing report from NASA astronauts has revealed that the background noise generated by such sources can interfere with speech communication in the work and living spaces of the craft.[1] Speech interference in such an environment could compromise safety and degrade performance of mission tasks. Therefore it is important to develop a method for evaluating the effect that proposed space station design and operations will have on speech communication.

The computer-based SSINAP model combines a Statistical Energy Analysis (SEA) prediction of the space station vibroacoustic environment with a speech intelligibility model based on the Modulation Transfer Function and Speech Transmission Index (MTF/STI). The latter model provides an appropriate state-of-the-art method for evaluating speech communication in the relatively reverberant and potentially noisy environments of space stations. The SEA model provides a corresponding effective analysis tool for evaluating the acoustic environments in such spaces. The result is a powerful combination of two diverse analysis tools that provide a practical systems approach to the problem of optimizing acoustic design of space stations from the standpoint of speech communications.

Section 2 of this report discusses the SEA methodology. It explains how a simplified model of a space station is defined in terms of its components and the scheme for evaluating the propagation of noise and vibration through the various parts of the craft. SSINAP uses the SEA algorithms to predict the background noise levels in all parts of the space station. Section 3 desribes the MTF/STI calculation which uses these levels to provide a quantitative measure of the acceptability of the predicted environment for effective speech communication. The appendix contains an explanation of the operation of SSINAP, along with details of the program structure and code.

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2.0 STATISTICAL ENERGY ANALYSIS (SEA)

Modeling the transmission of noise and vibration energy between a space station's structural elements, air-spaces, and varied noise and vibration sources is difficult because the system is complex, being composed of many different elements coupled in a variety of ways. Transmission paths for acoustic energy emitted by any of the sources vary from direct propagation through the air to more complex paths involving series or parallel transmission paths through structures. In addition, a model must account for structure-borne vibration generated by mechanical unbalance forces in rotating machinery and other equipment.

These complex transmission paths can be modeled effectively in terms of flow of acoustic and vibration power between coupled parts of the system. The statistical energy analysis method is useful for evaluating such complex transmission paths, especially at frequencies well above the fundamental frequency of the structure. In this case, the structure can be broken down into a manageable number of simple structural elements such as plates and beams, coupled acoustically to adjacent acoustic spaces or structurally to other structures. A very useful overview of the SEA method is provided in Reference 2.

2.1 Model Formulation

The general approach taken here is to consider the structure of a hypothetical space station to be composed of subsystems, consisting of structural elements or room volumes, each containing an unknown amount of vibratory or acoustic energy, each dissipating power at a known rate, and each interacting and exchanging mechanical vibration or acoustic power with neighboring subsystems. Power balance equations describing these power flows are set up in which the unknown variables are either a mean square velocity of a structural panel or the reverberant sound pressure in an acoustic space. These equations also contain powers injected into the system in terms of acoustic or mechanical excitation.

Each subsystem contains one unknown quantity and a power balance equation can be established for each subsystem. This results in a system of N linear equations in N unknowns (N = number of subsystems) which can be solved using well-known methods of linear algebra. The solution then defines the vibroacoustic power balance of the system, in terms of mean square structural velocities or mean square acoustic pressures of each subsystem, for the specified input powers. The following summary of the SEA model employed in this study is based primarily on the material in References 2 and 3.

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In general, the steady-state power balance equations take the following form:

$$W_i^{in} = W_i^d + \sum_j W_{i-j} \qquad (2-1)$$

where   W represents acoustic or vibrational power, and

the subscript "i" identifies the subsystem for which this power balance is written,

the subscript "j" includes all other subsystems,

the superscript "in" refers to the input power, and

the superscript "d" refers to dissipated power.

In words, the above equation reads:

The power injected to the i'th subsystem must be equal to the power dissipated in this subsystem plus the sum of all net power flows from this subsystem to all other subsystems. This power balance concept is illustrated in Figure 1.

While input and dissipated powers are always positive quantities, W_{i-j} may be positive or negative depending on the direction of the net power flow.

2.2   Stored and Dissipated Energy in a Subsystem

The following notation is used in the subsequent text (for convenience, the mks, meters-kilograms-seconds, system of units is used throughout):

E_i =   total energy in the i'th subsystem, joules

ω =   circular frequency, radian/sec

η_i =   loss factor in the i'th subsystem, dimensionless

$\langle p^2 \rangle$ =   space-time average of square of reverberant sound pressure, (Pascals)^2

$\langle v^2 \rangle$ =   space-time average of square of panel velocity, (meters/sec)^2

n   =   modal density, modes/radian

ρc =   characteristic acoustic impedance, Pascal sec/meter

c   =   speed of sound, meters/sec

V   =   volume of acoustic space, cubic meters

S   =   surface of panel or acoustic space, square meters
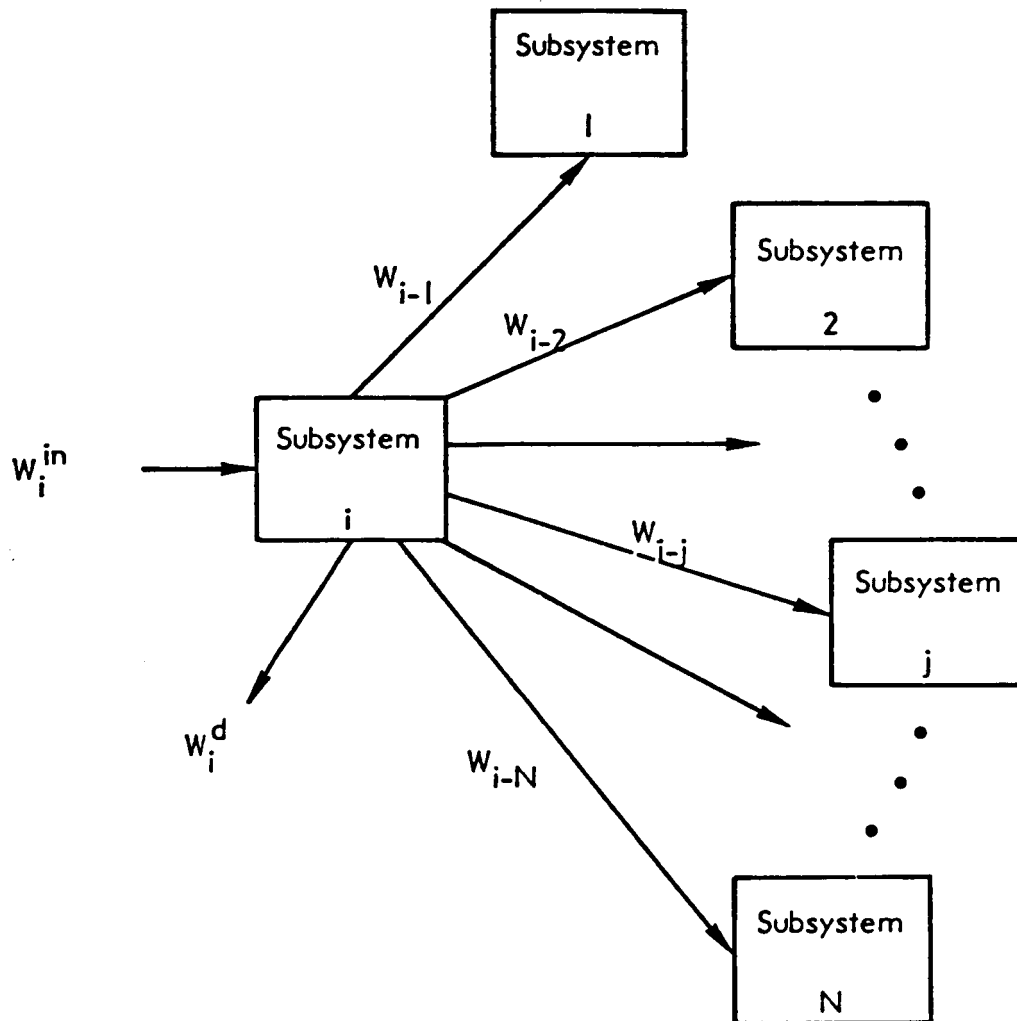
Figure 1. Schematic of Subsystem Power Flow (Statistical Energy Analysis).

ρ = panel mass density, kg/cubic meter

t = panel thickness, meters

C_L = longitudinal wave speed in panel material, meters/sec

$\overline{\alpha}$ = average absorption coefficient in acoustic space, dimensionless

Power flow between two subsystems is proportional to the difference in stored energy in the two subsystems and to the frequency. The total energy stored in a given subsystem, E, is related to the subsystem's characteristic properties as follows:

- For any structural element: $E = \langle v^2 \rangle \rho t S$ (2-2)

- For acoustic spaces: $E = \langle p^2 \rangle V/\rho c^2$ (2-3)

The dissipated power for a given subsystem, W^d, can be expressed as:

- For structural elements: $W^d = E \omega \eta = \langle v^2 \rangle \rho t S \omega \eta$,   (2-4)

- For acoustic spaces: $W^d = \langle p^2 \rangle \left(-S \ln (1 - \overline{\alpha}) \right)/(4 \rho c)$,   (2-5)

The energy stored in a structure or radiated by it may be thought of as being contained in the resonant modes of the structure. Assuming that energy is distributed equally among all modes the power stored or radiated will be the product of the energy in an "average" mode and the number of modes in the frequency band of interest:

$$E = E_m \, n(\omega) \qquad (2-6)$$

where E_m = modal energy

$n(\omega)$ = modal density = number of modes in band centered at ω

Following Reference 2, the power flow between the i'th and j'th system is given by:

$$W_{i-j} = \omega \eta_{i-j} (E_i - E_j \, n_i/n_j) \qquad (2-7)$$

where η_{i-j} is the coupling loss factor, which obeys the relation:

$$\eta_{i-j} = \eta_{j-i} \, n_j/n_i \qquad (2-8)$$

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2.3 Subsystem Coupling and Loss Factors

Coupling loss factors depend on the nature of the interaction between subsystems. The following defines those factors needed to determine the transmission loss of vibratory bending waves in structural elements:[3]

$$\eta_{i-j} = \frac{t_j \, \rho_j \, S_j}{t_i \, \rho_i \, S_i} \, T_{ij} \qquad (2-9)$$

where T_{ij} is the transmisson coefficient calculated using the relations below. In all cases the parameter σ is given by:

$$\sigma = t_j/t_i \quad \text{(thickness ratio)}$$

2.3.1 Junctions Between Panels

2.3.1.1 T-Junction
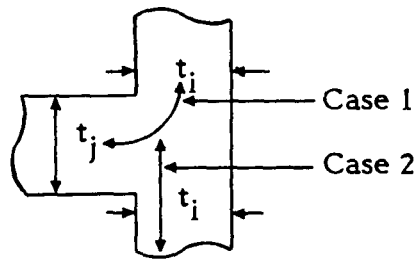
(a) Transmission around the bend of the T:

$$T_{ij} = \frac{2}{\left(\sigma^{5/2} + 2\,\sigma^{-5/4}\right)^2} \qquad (2-10)$$

(b) T-junction, transmission across the top of the T:

$$T_{ij} = \frac{1}{2 + 2\,\sigma^{5/2} + \frac{1}{2}\,\sigma^5} \qquad (2-11)$$

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2.3.1.2   L-Junction
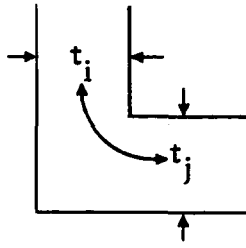
$$T_{ij} = \frac{2}{\left(\sigma^{-5/4} + \sigma^{5/4}\right)^2} \qquad (2\text{-}12)$$

2.3.2 Coupling From a Panel to an Acoustic Space
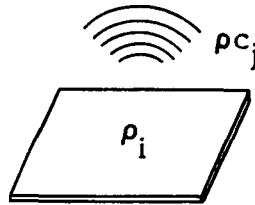
$$\eta_{i\text{-}j} = (\rho c)_j \, \sigma_{rad} / (\rho_i \, t_i \, \omega) \qquad (2\text{-}13)$$

where σ_{rad} is the radiation efficiency, which is a function of frequency and geometry. It is dependent on the critical frequency, f_c, of the panel at which the acoustic and panel bending waves coincide:

$$f_c = \frac{c^2}{1.8 \; C_L \, t}$$

The average radiation ratio of one side of a panel is given by the relations in Table 1.[4]

2.3.3 Coupling From an Acoustic Space to a Panel

This is the reverse of Section 2.3.2.   The following relation, given earlier, may be used:

$$\eta_{i\text{-}j} = \eta_{j\text{-}i} \; n_j / n_i$$

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Table 1

Radiation Ratios for Plane and Cylindrical Structures[4]

Structure Type	Radiation Ratio		
Rectangular panel or circular plate	$\sigma_{rad} \approx \left(1 - \dfrac{f_c}{f}\right)^{-\frac{1}{2}}$		for $f > f_c$
	$\approx \dfrac{4}{\pi^2} \cdot \dfrac{\lambda_c P}{S} \cdot \sin^{-1}\left(\dfrac{f}{f_c}\right)^{\frac{1}{2}}$		for $f \leq f_c$
Cylindrical shell	$\sigma_{rad} \approx \left(1 - \dfrac{f_c}{f}\right)^{-\frac{1}{2}}$		for $f > f_c$
	$\approx \dfrac{4}{\pi^2} \cdot \dfrac{\lambda_c P}{S} \cdot \sin^{-1}\left(\dfrac{f}{f_c}\right)^{\frac{1}{2}}$		for $f_r < f < f_c$
	$\approx \dfrac{\sqrt{3}}{2\beta}\left(\dfrac{f}{f_r}\right)^{3/2} \cdot \dfrac{f_r}{f_c}$		for $f < f_r < f_c$

f_c = critical frequency = $c^2/1.8\, c_L\, t$

f_r = ring frequency = $c_L/2\pi r$

λ_c = critical wavelength = c/f_c

S = area of structure

P = perimeter of structure

$\quad$ = $2(l + w)$ $\quad$ for a rectangular panel

$\quad$ = $2\pi r$ $\quad$ for a circular plate

$\quad$ = $2(2\pi r + l)$ $\quad$ for a cylindrical shell

$\quad l$ = length of rectangular panel or height of cylindrical shell

$\quad w$ = width of rectangular panel

$\quad r$ = radius of circular plate or cylindrical shell

β = $2.5\sqrt{f/f_r}$ $\quad$ for $f < 0.5\, f_r$

$\quad$ = $3.6\, f/f_r$ $\quad$ for $0.5\, f_r < f < 0.8\, f_r$

2.3.4 Coupling Between Two Acoustic Spaces

Two cases are distinguished; a direct connection through an aperture, and mass-controlled transmission ("mass law").

2.3.4.1 Aperture

$$\eta_{i-j} = \frac{\text{Area of Aperture}}{(\text{Wall Area})_i} \cdot \tau \qquad (2\text{-}14)$$

where τ depends on the value of kr:

$$kr = \frac{2\pi f}{c} r_{ap}$$

and r_{ap} = radius of the aperture.

When $t/r_{ap} \approx 0$ (the aperture radius is much greater than the panel thickness),

$$\tau = \begin{cases} 0.63095 \; ; & kr < 1.5 \\[2mm] 10^{1/10\,(-2.8268\,+\,4.7\,\log\,k\,r_{ap})} ; & 1.5 < kr < 4.0 \\[4mm] 1.0 \qquad ; & kr > 4.0 \end{cases}$$

2.3.4.2 Mass Law

Whenever a panel (plate, floor, ceiling, wall) separates two acoustic spaces, the approach discussed here considers two types of power flow between those spaces:

- Transmission via resonant modes in the panel (resonant panel response)
- Traditional mass law transmission (forced, non-resonant response)

The first type is taken care of by applying Sections 2.3.2 and 2.3.3, above, appropriately. The second type of flow needs special consideration as follows.

In order to use the same formalism as for the other cases, the power flow from one space to the other is expressed in the form:

$$W_{i-j} = E\,\omega\,\eta_{i-j}$$

The acoustic power W transmitted into a volume V through a wall of area S having a transmission coefficient τ can be defined by:

$$W = \tau S \frac{E c}{4 V}$$

where E is the acoustic energy in the source room. The transmission coefficient τ, according to a simple mass law, is given by:

$$\tau = \frac{0.316}{1 + \left(\frac{\omega \rho t}{2 \rho c}\right)^2} \qquad (2\text{-}15)$$

(The 0.316 factor corrects the normal incidence expression to "field" incidence transmission loss (i.e., -5 dB).[2])

Setting the two expressions for W equal, results in:

$$\eta_{i\text{-}j} = \tau \frac{S c}{4 \omega V} \qquad (2\text{-}16)$$

As an aside, note the similarity of the mathematical formulation between this coupling loss factor (which does not involve any modal densities) and the one used for resonant structural modes in Equation (2-8) (which involves modal densities n). That is, a mass law coupling factor can be defined as:

$$\text{mass law:} \qquad \eta_{i\text{-}j} = \eta_{j\text{-}i} \frac{V_j / c_j}{V_i / c_i} \qquad (2\text{-}17)$$

whereas the coupling factor for resonant modes is:

$$\eta_{i\text{-}j} = \eta_{j\text{-}i} \frac{n_j}{n_i}$$

This similarity can usefully be exploited in coding a general computer program which uses this SEA model.

2.4 Modal Densities

Modal densities for subsystems are calculated according to the following formulae.

2.4.1 Panels

For rectangular panels, the modal density is given by:[2]

$$n(f) = \frac{\sqrt{12}}{4\pi} \, S/(C_L \, t) \tag{2-18}$$

where S is the panel area.

For cylindrical shells, the model density is given by:[5]

$$n(f) = \frac{\sqrt{3}}{2} \frac{l\,r}{C_L\,t} \left[\frac{\sqrt{2\nu}}{\pi} \, K\left(\sqrt{\frac{\nu+1}{2}}\right) \right] \quad ; \quad \nu < 1$$

$$\tag{2-19}$$

$$= \frac{\sqrt{3}}{2} \frac{l\,r}{C_L\,t} \left[\frac{2}{\pi\sqrt{1+\frac{1}{\nu}}} \, K\left(\sqrt{\frac{2}{\nu+1}}\right) \right] \quad ; \quad \nu > 1$$

where
ν = normalized frequency = $2\pi f r/C_L$

l = height of cylinder

r = radius of cylinder

t = thickness of shell

C_L = longitudinal wave speed

$K(m)$ = complete elliptic integral of the first kind.

The function $K(m)$ can be approximated by:[6]

$$K(m) \approx 1.3862944 + 0.1119723\,m_1 + 0.0725296\,m_1^2$$

$$+ \left[0.5 + 0.1213478\,m_1 + 0.0288729\,m_1^2 \right] \ln\left(\frac{1}{m_1}\right)$$

where $m_1 = 1 - m$.

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For circular plates, the modal density is given by:[4]

$$n(f) = \frac{4\sqrt{3}\,r^2}{\pi^2\,C_L\,t} \tag{2-20}$$

where r = radius of plate

       t = thickness of plate

      C_L = longitudinal wave speed

2.4.2 Acoustic Spaces

For a rectangular acoustic space formed by rectangular panels, the model density is given by:[7]

$$n(f) = \frac{2\,f^2\,V}{c^3} + \frac{f\,S}{4\,c^2} \tag{2-21}$$

where v = volume of the space

      S = surface area of the space

      c = speed of sound.

For a cylindrical acoustic space formed by a cylindrical shell and circular plates, the model density is given by:[7]

$$n(f) = \frac{1}{2\pi}\left[\frac{4\pi\,f^2\,V}{c^3} + \frac{\pi\,f\,S}{2\,c^2} + \frac{L}{8\,c}\right] \tag{2-22}$$

where V = volume of the space

      S = surface area of the space

      c = speed of sound

      L = $4\pi r + 4l$

      r = radius of the shell and plate

      l = height of the shell

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2.5   Input Powers

Sound and vibration enter the space station as power inputs to one or more subsystems. This acoustic and vibrational power data may be entered into SSINAP in a generic fashion by providing for each source either the power (in watts) or the power level (in dB re 1 picowatt) in each of nine octave bands centered from 31.5 to 8000 Hz.

Alternately, provision has been built into SSINAP to calculate the airborne acoustic power or the structureborne vibrational power for a set of possible sound and vibration sources. This set of sources includes:

- Duct diffusers and compressors for HVAC systems;
- AC and DC electric motors;
- Ventilation and equipment cooling fans; and
- Centrifugal pumps.

The algorithms used for the calculation of the acoustic and vibrational power from each of these sources are based upon functional relationships and empirical data contained in Reference 8, which provides equations for the prediction of airborne acoustic power levels and structureborne vibrational acceleration levels from various types of shipboard equipment. The algorithms used in SSINAP employ the acoustic power prediction equations directly. The predicted vibrational acceleration levels from Reference 8, however, are first converted to vibrational velocity levels using the relation:

$$L_v = L_a - 20 \log_{10} \omega + 60 \qquad (2\text{-}23)$$

where L_v is the velocity level in dB re 10 nanometers/sec,

L_a is the acceleration level in dB re 10 micrometers/sec^2, and

ω is the circular frequency,

These velocity levels are then converted to vibrational power levels using the relation (based on the power applied to a system by a point force[4]):

$$L_w = L_v + 10 \log (1.15\, C_L\, \rho\, t^2) - 40 \qquad (2\text{-}24)$$

where L_w is the power level in dB re 1 picowatt,

C_L is the longitudinal wave speed of the panel in m/sec,

ρ is the density of the panel material in kg/m^3, and

t is the panel thickness in meters.

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Section 2.5.1 describes the algorithms used to predict the airborne acoustic power levels from the sources listed above; Section 2.5.2 describes the algorithms used to predict the structureborne vibrational power levels for these sources.

2.5.1 Airborne Acoustic Power Levels

In the equations below, all acoustic power levels, L_w, are in dB re 1 picowatt.

2.5.1.1 HVAC System (Duct Diffuser)

$$L_w(f) = 10 \log_{10} \left[S\, (\Delta P)^3 / V^6 \right] + A(f) \log_{10} V + B(f) \qquad (2\text{-}25)$$

where S is the cross-sectional area of the duct in m^2,

ΔP is the pressure drop across the diffuser in Pa,

V is the air flow speed in m/sec, and

the coefficients $A(f)$ and $B(f)$ are given by:

Octave Band Center Frequency (Hz)	2 m/sec $\leq$ V $\leq$ 6 m/sec		6 m/sec $\leq$ V $\leq$ 20 m/sec	
	A	B	A	B
31.5	34.35	11.4	33.65	12.0
63	40.42	13.6	33.65	19.0
125	48.50	14.2	33.65	26.0
250	44.46	17.4	47.51	15.0
500	60.62	13.7	41.57	28.7
1000	72.75	4.8	47.51	25.0
2000	74.77	0.2	61.37	11.0
4000	82.85	-9.2	61.37	8.0
8000	82.85	-15.2	67.31	-2.8

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2.5.1.2 Electric Motors

$$L_w(f) \; = \; 13 \log_{10} W \; + \; 15 \log_{10} R \; + \; \Delta(f) \tag{2-26}$$

where W is the rated power of the motor in watts,

R is the rated speed of the motor in RPM, and

$\Delta(f)$ is given by:

Motor Type	Octave Band Center Frequency (Hz)								
	31.5	63	125	250	500	1000	2000	4000	8000
AC	-37.3	-36.3	-32.3	-28.3	-27.3	-27.3	-28.3	-34.3	-41.3
DC	-42.3	-42.3	-37.3	-32.3	-27.3	-27.3	-28.3	-34.3	-41.3

2.5.1.3 Fans

$$L_w(f) \; = \; 10 \log_{10} \left[V \, (\Delta P)^2 \right] \; + \; \Delta(f) \tag{2-27}$$

where V is the volume flow through the fan in m^3/sec,

ΔP is the pressure change across the fan in Pascals, and

$\Delta(f)$ is given by:

Fan Type	Blade Passage Correction*	Octave Band Center Frequency (Hz)								
		31.5	63	125	250	500	1000	2000	4000	8000
Centrifugal:										
Airfoil	5	21.3	24.3	23.3	21.3	15.3	12.3	9.3	4.3	0.3
Backward Curve	5	21.3	26.3	22.3	22.3	21.3	20.3	15.3	11.3	6.3
Forward Curve	0	27.3	35.3	31.3	26.3	21.3	16.3	13.3	11.3	8.3
Radial	6	36.3	40.3	35.3	33.3	26.3	25.3	21.3	21.3	20.3
Tubular	5	35.3	31.3	24.3	25.3	22.3	22.3	18.3	17.3	11.3
Axial:										
Vane Axial	4	29.3	31.3	32.3	33.3	33.3	33.3	31.3	27.3	26.3
Tube Axial	4	30.3	27.3	29.3	32.3	32.3	30.3	30.3	25.3	22.3
Propeller	5	38.3	35.3	34.3	33.3	32.3	30.3	29.3	27.3	16.3

* To be added to octave band containing the blade passage frequency:

$f_B = n_B R$; n_B = number of blades on fan; R = rated speed in rev/sec.

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2.5.1.4 Centrifugal Pump

$$L_w = 10 \log_{10} W + 15 \log_{10} R + \Delta(f) \qquad (2\text{-}28)$$

where   W is the rated power of the pump drive motor in watts,

R is the rated speed of the pump, and

$\Delta(f)$ is given by:

Octave Band Center Frequency (Hz)								
31.5	63	125	250	500	1000	2000	4000	8000
11.3	11.3	12.3	12.3	13.3	15.3	12.3	9.3	4.3

2.5.2 Structureborne Vibrational Power Levels

In the equations below, all vibrational power levels, L_w, are in dB re 1 picowatt. In addition, the following parameters are common throughout the set of equations:

C_L = longitudinal wave speed in the panel in m/sec,

ρ = density of the panel material in kg/m^3, and

t = thickness of the panel in m.

2.5.2.1 HVAC System (Reciprocating Compressor)

$$L_w(f) = 10 \log_{10} (C_L \, \rho \, t^2 \, W) + \Delta(f) \qquad (2\text{-}29)$$

where   W is the rated power of the drive motor in watts, and

$\Delta(f)$ is given by:

Mount Type	Octave Band Center Frequency (Hz)								
	31.5	63	125	250	500	1000	2000	4000	8000
Hard	21.0	21.9	19.0	12.0	4.0	0.9	-8.1	-17.1	-20.1
Soft	21.0	21.9	19.0	11.0	2.0	-2.1	-12.1	-21.1	-24.1

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2.5.2.2 Electric Motor

$$L_w(f) = 10 \log_{10}(C_L \rho t^2) + \Delta(f) \qquad (2\text{-}30)$$

where $\Delta(f)$ is given by:

Motor Type	Mount Type	Octave Band Center Frequency (Hz)								
		31.5	63	125	250	500	1000	2000	4000	8000
AC	Hard	60.7	54.6	48.7	42.7	36.7	30.6	24.6	18.6	12.6
AC	Soft	60.7	54.6	48.7	41.7	34.7	27.6	20.6	14.6	8.6
DC	Hard	42.7	37.6	32.7	30.7	27.7	22.6	12.6	7.6	2.6
DC	Soft	42.7	37.6	32.7	29.7	25.7	19.6	8.6	3.6	-1.4

2.5.2.3 Fans

Ventilation and equipment cooling fans are generally resiliently mounted and produce insignificant amounts of structureborne vibrational power. If this is not the case, acceleration levels should be obtained from the vendor and used to compute acceleration power levels by applying Equations (2-23) and (2-24). These power levels can then be input into SSINAP using the generic power level entry option.

2.5.2.4 Centrifugal Pumps

$$L_w(f) = 10 \log_{10}(C_L \rho t^2 W) + \Delta(f) \qquad (2\text{-}31)$$

where W is the rated power of the drive motor in watts, and

$\Delta(f)$ is given by:

Mount Type	Octave Band Center Frequency (Hz)								
	31.5	63	125	250	500	1000	2000	4000	8000
Hard	0.0	1.9	9.0	1.0	-1.0	-6.1	-16.1	-18.1	-25.1
Soft	0.0	1.9	9.0	0.0	-3.0	-9.1	-20.1	-22.1	-29.1

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3.0 PROCEDURE FOR CALCULATING THE SPEECH TRANSMISSION INDEX

Based on a systematic study of the combined effects of reverberation and interfering noise on speech intelligibility, Houtgast and Steeneken developed a model that successfully predicts intelligibility scores for a wide variety of listening conditions in noisy, reverberant conditions.[9,10] According to this model, any speech-transmission channel is characterized physically by its Modulation Transfer Function (MTF), and from this function a relevant index, the Speech Transmission Index, can be derived. This index is found to provide a suitable objective method for estimating speech intelligibility.

As shown by Houtgast and Steeneken, it is also possible to calculate the MTF for acoustic conditions in a room specified in general terms, such as the volume and reverberation time of the room, the talker-to-listener distance, and the interfering-noise level.

As illustrated in Figure 2, the Modulation Transfer Function (MTF) specifies the degradation of the modulation index of a 100-percent intensity-modulated signal, transmitted from source to receiver (talker to listener), as a function of modulation frequency (F). This function reflects the combined effects of reverberation and interfering noise.

The signal arriving at the receiver's position is assumed to consist of three parts which are additive in terms of intensity: the interfering noise, the direct signal, and the reverberant signal, the latter being assumed to be associated with an ideally exponential reverberation process. The specific algorithms employed in this study for computing MTF and STI are specified in the following text. The end product is an average speech transmission index ($\overline{\text{STI}}$) computed by the parameters in Table 2.
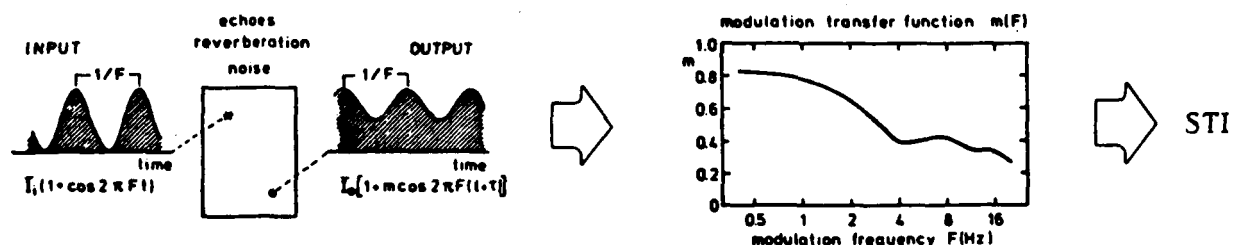
Figure 2. Conceptual Illustration of How the Speech Transmission Index for Any Speech Transmission Path is Derived From the Modulation Transfer Function — A Measure of the Degree of Preservation of an Idealized Model for Fluctuations in the Envelope of a Speech Signal. (From Houtgast.[9])

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Table 2

Parameters for Calculating Speech Transmission Index

Symbol	Units	Description
f	Hz	Octave band center frequency for the speech spectrum. The four octave band center frequencies in this analysis are 500, 1000, 2000, and 4000 Hz.
F	Hz	Octave band center frequency for the modulation spectrum. The six modulation frequencies are 0.5, 1, 2, 4, 8, and 16 Hz.
$S(f)$	dB	Long-term energy average (L_{eq}) Speech Plus Noise Signal Level in the four analysis octave bands at the measurement location.
$S'(f)$	dB	Long-term energy average (L_{eq}) Speech Signal Level (without noise) in each of the four analysis octave bands at the measurement location.
$N(f)$	dB	Long-term energy average (L_{eq}) Sound Level of the ambient noise in each of the four analysis octave bands at the measurement location.
$SN(f)$	dB	Signal-to-Noise Ratio in each of the four analysis octave bands.
$\overline{\alpha}(f)$	--	Average absorption coefficient in each of the four analysis octave bands.
A_w	m^2	Wall area of the air space for which the STI is to be calculated.
V	m^3	Volume of the air space for which the STI is to be calculated.
r_s	m	Distance from the listener to the signal source.
r_c	m	Critical radius of each test room based on the Average Reverberation Time $\overline{T}$.
c	m/sec	Speed of sound.
P	%	Percent confidence interval for each given age group of listeners.
AGE	years	Age of designated listener group.
Q_s	--	Directivity factor of the signal source at the listener's position.
Q_l	--	Directivity factor of the listener.*

* See Appendix A for discussion of recommended values for Q_l.

3.1 Critical Radius

The critical radius, $r_c(f)$, of the signal source in the air-space for each analysis frequency is given by:

$$r_c(f) = \sqrt{\frac{A\,\overline{\alpha}}{16\,\pi\,(1-\overline{\alpha})}}\quad,\quad \text{meters} \qquad (3\text{-}1)$$

3.2 Signal-to-Noise Ratio

The signal-to-noise ratio, $SN(f)$, for each analysis frequency is given by:

$$SN(f) = 10 \log\left[10^{\left(\frac{S(f)\,-\,N(f)}{10}\right)} - 1\right]\quad,\quad dB \qquad (3\text{-}2)$$

Note that:

a. $S(f)$ represents the total signal corresponding to speech plus noise.

b. Since the log term in Equation (3-2) becomes indeterminate for $S(f) \leq N(f)$, the convention was selected to set the difference $S(f) - N(f) = 0.001$ whenever $S(f) \leq N(f)$.

Further note that:

a. When dealing with a speech signal only (i.e., using $S'(f)$ instead of $S(f)$), Equation (3-2) simplifies to:

$$SN(f) = S'(f) - N(f)$$

3.3 Modulation Transfer Function

The Modulation Transfer Function, $m(F,f)$, at each of the six speech modulation octave band frequencies, F, and at each of the four speech signal octave band frequencies, f, is given by:[9]

$$m(F,f) = \frac{\left(A^2 + B^2\right)^{\frac{1}{2}}}{C} \qquad (3\text{-}3)$$

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$$\text{where} \quad A = \frac{Q_s \cdot Q_1 \cdot r_c^2}{r_s^2} + \frac{1}{(1 + D^2)} \tag{3-3a}$$

$$B = \frac{D}{(1 + D^2)} \tag{3-3b}$$

$$C = \left[\left(\frac{Q_s \cdot Q_1 \cdot r_c^2}{r_s^2} \right) + 1 \right] \left(1 + 10^{-SN(f)/10} \right) \tag{3-3c}$$

$$D = \frac{8 \pi F V}{A_w c \, \bar{\alpha}(f)} \tag{3-3d}$$

3.4 Effective Signal-to-Noise Ratio

The effective signal-to-noise ratio, $ESN(F, f)$, at each of the modulation and speech octave band frequencies is given by:[9]

$$ESN(F, f) = 10 \log \left(\frac{m(F, f)}{1 - m(F, f)} \right), \quad dB \tag{3-4}$$

These results are limited to a ± 15 dB range by requiring:

$$ESN(F, f) \equiv +15 \text{ dB} \quad \text{for} \quad ESN(F, f) > 15 \text{ dB}$$

$$ESN(F, f) \equiv -15 \text{ dB} \quad \text{for} \quad ESN(F, f) < -15 \text{ dB}$$

3.5 Speech Transmission Index Age Discount

An age speech intelligibility/hearing discount factor, DSTI, is given by:[11]

$$DSTI = \left[\frac{2 \log (100 - P) - 4.9}{0.3 \, (AGE) - 30} \right] - \frac{1}{15} \tag{3-5}$$

where P is a whole number in percent.

3.6 Speech Transmission Index

The Speech Transmission Index, STI(f), in each analysis frequency is given by: [9]

$$STI(f) = \left[\frac{1}{6} \left[\sum_{F=0.5}^{F=16} ESN(F,f) \right] + 15 \right] \left(\frac{1}{30} \right) - DSTI \qquad (3-6)$$

The convention has been adopted that $STI(f) = 0.00001$ for $STI(f) \le 0$.

3.7 Average Speech Transmission Index

The Average Speech Transmission Index, $\overline{STI}$, is given by: [10]

$$\overline{STI} = \sum_{f=500}^{f=4000} a(f) \cdot STI(f) , \quad \% \qquad (3-7)$$

where
$$a(500) = 19.5$$
$$a(1000) = 19.5$$
$$a(2000) = 32.0$$
$$a(4000) = 29.0$$

are weighting factors derived from consideration of the relative importance of these speech frequency bands for intelligibility. Note that the convention is employed of expressing $\overline{STI}$ as a percentage (from 0 to 100), while $STI(f)$ is a fraction (from 0 to 1).

3.8 Speech Intelligibility

Just as for the Articulation Index, the Speech Transmission Index provides an objective measure for predicting speech intelligibility. The latter quantity can be evaluated by subjective tests in terms of several different measures of speech communication including:

- Intelligibility of Phonetically Balanced (PB) words
- Sentence Intelligibility

The following algorithms are available to relate STI values to PB word scores and hence provide estimates of sentence intelligibility (SI). However, these subjective speech intelligibilty scores are recognized as being highly dependent on the information content

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of the words or sentences employed and the training of the test subjects, so they were not included in the SSINAP computer program. As a rough rule of thumb, STI scores (after correction for the "age discount" in Equation (3-5)) of about 0.45 should provide a high degree of speech intelligibility in any noisy, reverberant space.

The PB Word Score (PBWS) in percent can be calculated by:[12]

$$PBWS = -0.000124 \, \overline{STI}^3 - 0.00312 \, \overline{STI}^2 + 2.80 \, \overline{STI} - 43.0 \; , \; \% \qquad (3\text{-}8)$$

and the sentence intelligibility, SI, in percent can be estimated as follows:[13]

For PBWS < 30% ,

$$SI = 3.8 + 1.80 \, PBWS + 0.174 \, PBWS^2 - 4.73 \times 10^{-3} \, PBWS^3 , \; \% \qquad (3\text{-}9a)$$

For PBWS ≥ 30,

$$SI = 72.0 + 0.846 \, PBWS - 9.82 \times 10^{-3} \, PBWS^2 + 4.18 \times 10^{-5} \, PBWS^3 , \; \% \qquad (3\text{-}9b)$$

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4.0 SUMMARY

In summary, an SEA analysis involves the following steps:

1. Divide the space station into structural or acoustical subsystems which can be modeled in terms of energies contained in narrow frequency bands.

2. Determine the power inputs to the subsystems in terms of the strength of acoustic sources and mechanical power injected by motors, pumps, etc.

3. Determine the power lost within each subsystem due to sound absorption (Equation (2-5)) or panel internal damping and interface friction (Equation (2-4)).

4. Determine the power flows between subsystems (Equation (2-7)). This requires knowledge of each subsystem's characteristic data in order to calculate energies (Equations (2-2) and (2-3)), modal densities (Equations (2-18) and (2-19)), and coupling loss factors (Equations (2-9) through (2-16)).

5. Set up the system of equations as given by Equation (2-1), one equation for each subsystem of the structure, and solve for the unknown panel velocities and acoustic pressures in the reverberant field.

Then the STI calculation can be performed:

1. Identify the air-space subsystem targeted and input the necessary variables.

2. Calculate the Modulation Transfer Function at 0.5, 1, 2, 4, 8, and 16 Hz.

3. Compute the Average Speech Transmission Index. Estimates of Speech Intelligibility can be made from STI using the algorithms in Section 3.8.

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APPENDIX A

User's/Programmer's Manual

A.1 INTRODUCTION

The Space Station Interior Noise Analysis Program (SSINAP) is a computerized model for evaluating space station interior noise and vibration. The program makes a systematic prediction of the noise and vibration environment of a user-defined craft and evaluates the relative acceptability of the predicted environment for effective speech communication. To accomplish this, the user describes the space station as a group of subsystems. Then SSINAP performs a statistical energy analysis (SEA) of the total vibroacoustic system in each of nine octave bands centered from 31.5 to 8000 Hz. This is coupled with a model for predicting speech intelligibility based on the Speech Transmission Index (STI). SSINAP computes the STI for any room in the space station.

SSINAP considers several different sources of vibroacoustic power into the system. The user may enter power directly or may choose from a menu of equipment sources including HVAC systems, AC and DC motors, pumps, and a variety of fans. Coupling between the subsystems accounts for structureborne vibration and air-to-air and air-to-structure energy transmission.

The program is interactive and user-friendly, prompting the user for all necessary input and checking for errors and omissions. The user has the option of entering all the information at the terminal or using supplementary input files. In addition, the system description data set can be saved on disk for subsequent use as input. All results can be printed in an 8½- by 11-inch format. The source code is written in Microsoft FORTRAN without proprietary or assembly language routines and is fully annotated. SSINAP operates under the Microsoft Disk Operating System (MS-DOS) and runs on the IBM PC, DEC Rainbow, and Tandy 2000 computing systems.

This appendix provides the operating instructions for SSINAP and documents the software. Section A.2 is the User's Guide, providing an explanation of how to set up a space station description data set and instructions on operating SSINAP. Section A.3 forms a Programmer's Reference Guide and details the various program segments and variables used in SSINAP, along with the appropriate software configuration. Section A.4 provides a sample input file and the data printed from it.

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A.2 USER'S GUIDE

Since SSINAP prompts the user for all input, it can be operated with minimal supplemental documentation. This chapter describes how to set up a space station description data set for use in SSINAP and how to use the program's several options to predict the vibroacoustic environment and evaluate its effect on speech intelligibility.

The program was developed to be as error-proof as was practical. For example, all input is checked for inappropriate responses. Also, when attempting to read from or write to a disk file, SSINAP checks first to see if the file exists. When responding to a yes or no question, anything other than a "Y", including pressing "Return", is interpreted as meaning "no". In general, when modifying data, pressing "Return" keeps the current value. Exceptions to this pattern are noted in this guide. Before allowing the user to exit the program, SSINAP prompts the user to save any new data set.

Section A.2.1 describes program flow. Section A.2.2 explains data input and system modeling. The Statistical Energy Analysis is discussed in Section A.2.3. Then Section A.2.4 covers the Speech Interference Index. Output of results is discussed in Sections A.2.3 and A.2.4 with the computations.

A.2.1 Program Flow

A main menu controls the performance of SSINAP's several functions. On entering the program the user sees a list of options:

(1) Create a new subsystem data set

(2) Modify an existing data set currently in memory

(3) Write a data set from memory to disk

(4) Read a data set from a disk file

(5) Print a data set currently in memory

(6) Run the SEA module

(7) Run the STI module

(8) Return to the disk operating system

If Option (7) is chosen, an STI menu appears which controls operations within that module.

Because SSINAP requires specific blocks of information for most operations, the program reminds the user of data that must be entered or calculations that must be performed prior to proceeding with some menu operations.

Functions must be requested in the following order:

1. Enter a subsystem data set (Option (1), which is interactive, or Option (4)).

2. Modify or write subsystem data (Options (2), (3), or (5)). This can be done at any time after data is entered and is not prerequisite for any subsequent choices.

3. Perform statistical energy analysis of the entire vibroacoustical system (Option (6)). This must be done if SEA results were not read from a subsystem data set file or if the data set has been modified since being entered.

4. Enter STI data (Option (7), STI menu choice 1).

5. Calculate STI (Option (7), STI menu choice 3).

6. Print STI results (Option (7), STI menu choice 4).

This sequence may be repeated as desired. Any time a subsystem data set is modified the SEA results must be recomputed before the STI can be calculated.

A.2.2 Data Input – Modeling the System

The space station is completely described to the program by a data set which the user may create at the terminal, or which may be read from a disk file. In general, the initial description of a space station will be created at the terminal and saved on disk. Any subsequent modifications to the design will be defined by editing the original data set using Option (2). Each data set is identified by a descriptive title which appears on all printouts, along with the name of the disk file it was read from or written to. Any time a data set is modified the user enters a new title. Pressing "Return" in this case gives a blank title. The file name is cleared until the data set is written to a new disk file.

Section A.2.2.1, which follows, discusses separating the space station into subsystems and assigning properties to those subsystems. Section A.2.2.2 describes the connections coupling the subsystems together. The last section, A.2.2.3, covers power source inputs to the subsystems.

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A.2.2.1 Subsystems

In SSINAP a space station is modeled as a group of subsystems – structural elements and air-spaces. The program allows up to 20 subsystems. A connectivity matrix is used to define the types of subsystems and the coupling between them. The integers on the diagonal of the connectivity matrix indicate the subsystem type. The types are:

- -1 = rectangular panel
- -2 = rectangular air-space
- -3 = cylindrical air-space
- -4 = cylindrical shell
- -5 = circular plate

For example, in the connectivity matrix sample on page 9, elements 7 and 13 are air-spaces, and all the rest are panels. Section A.2.2.2 defines how the off-diagonal elements of the connectivity matrix are used to define the connections between subsystems.

A subsystem property matrix gives all the material properties (except absorption) and the dimensions of every subsystem in the model. These variables are:

Rectangular Air-Space

Volume
Surface area
Characteristic impedance
Sound speed
Pointer to absorption table

Cylindrical Air-Space

Length
Radius
Characteristic impedance
Sound speed
Pointer to absorption table

Rectangular Panel

Thickness
Length
Width
Longitudinal wave speed
Density
Damping factor
Aperture radius*

Cylindrical Shell

Thickness
Length
Radius
Longitudinal wave speed
Density
Damping factor
Aperture radius*

Circular Plate

Thickness
Radius
Longitudinal wave speed
Density
Damping factor
Aperture radius*

---

* Set to 0 if there is no aperture in the panel.

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Absorption tables provide absorption coefficients for the surfaces surrounding the air-spaces. There may be up to four unique tables, each with one coefficient per octave band. The absorption coefficient is applied to the entire surface of an air-space. These tables are accessed by pointers in the property matrix.

The three screen dumps which follow (Figures A-1, A-2, and A-3) show the input variables for structural elements, air-space subsystems, and absorption tables, respectively. Note that all facilitate modification of the data prior to continuing to the next data input step. When modifying the subsystem data, the program first asks if any data needs changing. Pressing the "Return" key is equivalent to a negative response. After an affirmative response the program asks which item number will be changed. Then the user enters a new value for that item. For changes in the absorption table SSINAP asks for the table number and the frequency of the coefficient to be changed. Both those responses appear within the brackets but each must be entered separately by pressing the "Return" key. Then the user enters a new absorption coefficient.

A.2.2.2 Connections

Connections between subsystems are indicated in the off-diagonal elements of the connectivity matrix by an integer index. Power flows through seven different types of couplings:

- 0 = no connection
- 1 = T-connection, power flows around bend through base
- 2 = T-connection, power flows across top bar
- 3 = L-connection
- 4 = panel-to-air
- 5 = air-to-panel

- 5 + (panel subsystem number) = $\begin{cases} \text{air-to-air through mass-law panel,} \\ \quad \text{if there is no aperture in the panel } (r_a = 0) \\ \text{air-to-air through an aperture in the panel,} \\ \quad \text{if one exists } (r_a \neq 0). \end{cases}$

In describing connections between two air-spaces separated by a panel, not only must the panel-to-air and air-to-panel resonant couplings (indicated by element values of 4 and 5, respectively) be defined, but also the non-resonant coupling due to mass law or aperture transmission must be defined. For example, referring to Figure A-4, if air-spaces 7 and 13 share a common wall, which is defined as subsystem number 4, then the

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```
**********  ENTER THE SUBSYSTEM PROPERTY MATRIX  ***********

********************  SUBSYSTEM  1  *********************


                SUBSYSTEM TYPE: RECTANGULAR PANEL

(1)                  THICKNESS:   .158800E-02 METERS

(2)                     LENGTH:   1.00000     METERS

(3)                      WIDTH:   1.00000     METERS

(4)     LONGITUDINAL WAVE SPEED:  6300.00     METERS/SEC

(5)                    DENSITY:   2700.00     KG/CUBIC METER

(6)                LOSS FACTOR:   .100000

(7)            APERATURE RADIUS:  .000000     METERS



       <<            ANY MODIFICATIONS?            >>
```

Figure A-1.   Input Variables for Structural Elements.

```
********** ENTER THE SUBSYSTEM PROPERTY MATRIX ***********

******************** SUBSYSTEM 7 *********************


                    SUBSYSTEM TYPE: RECTANGULAR SPACE

  (1)                      VOLUME:  1.00000      CUBIC METERS

  (2)                SURFACE AREA:  6.00000      SQUARE METERS

  (3)   CHARACTERISTIC IMPEDANCE:  415.000      PA SEC/METER

  (4)              SPEED OF SOUND:  343.000      METERS/SEC

  (5)POINTER TO ABSORPTION TABLE:       1




          <<          ANY MODIFICATIONS?              >>
```

Figure A-2. Input Variables for Air-Space Subsystems.

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```
********  ENTER THE ABSORPTION COEFFICIENT MATRIX  *********




TABLE              OCTAVE BAND CENTER FREQUENCY (HZ)
NUMBER  31.5    63   125   250   500  1000  2000  4000  8000
  1     .250  .250  .250  .250  .250  .250  .250  .250  .050




        << ENTER TABLE NUMBER AND FREQUENCY: ( 1, 8000 )   >>
```

Figure A-3. Input Variables for Absorption Tables.

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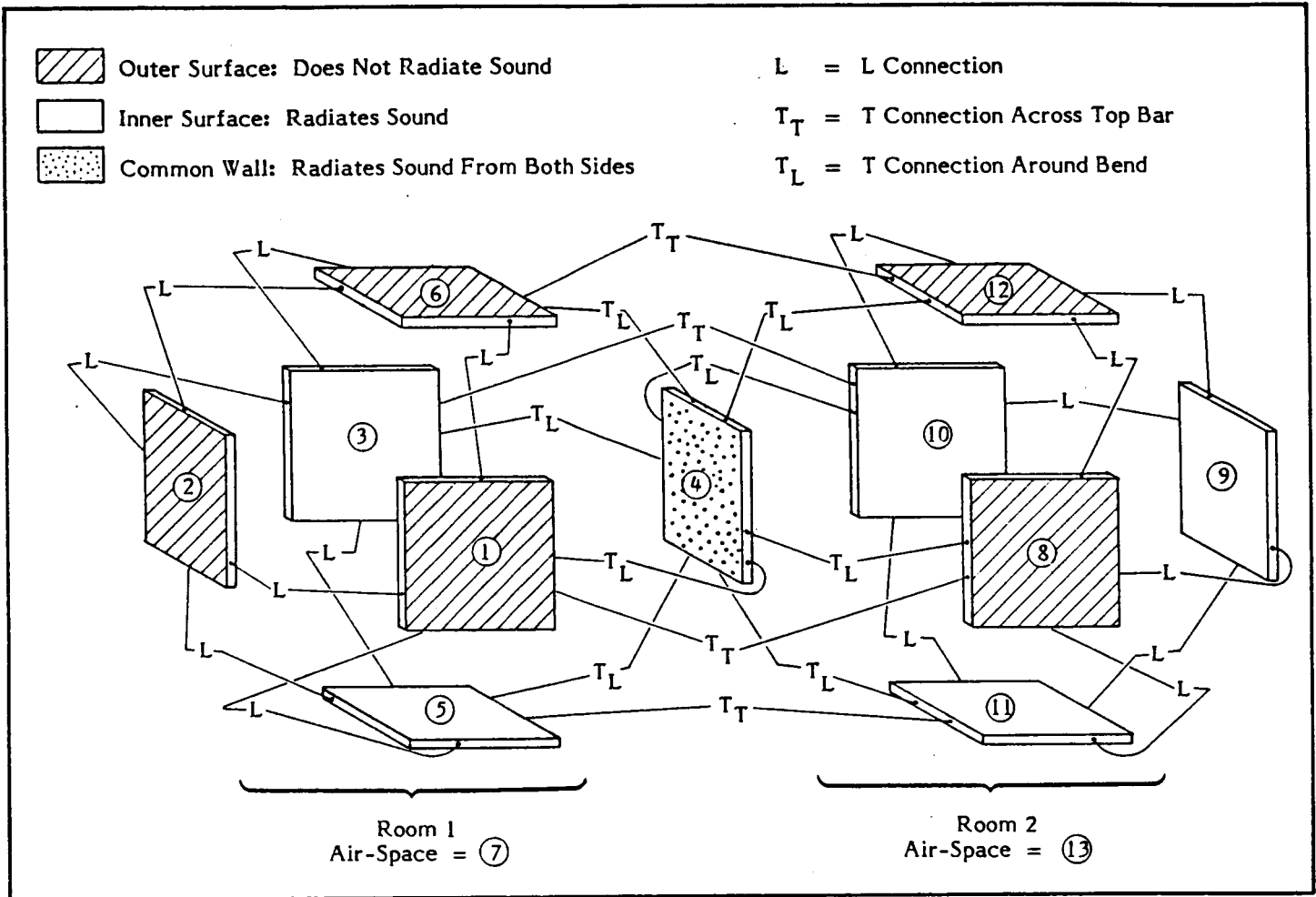
Figure A-4. Exploded View of Sample System Showing Panel Coupling.

user indicates an air-to-air mass-law coupling across panel 4 by entering a $5 + 4 = \underline{9}$ for the connectivity matrix element in row 7, column 13, and assigns a zero value to the aperture radius for subsystem 4.

When the user enters these matrix elements interactively, SSINAP automatically fills the half of the matrix below the diagonal from data entered for the upper half. During modification the program asks for a row and a column number. The user types the row and presses "Return", then types the column and "Return". After the user enters a new index, SSINAP adjusts both symmetric elements in the matrix.

Figure A-4 shows a sample system consisting of two adjacent rooms and the connections between each of the 13 subsystems. Since SSINAP does not know which air-spaces share a common wall, the user must indicate all instances where there may be mass-law sound transmission from one air-space to another through a panel. The sample connectivity matrix included with this user's guide describes the system in Figure A-4 and illustrates this type of connection between air-space subsystems 7 and 13. Note that the property matrix shows the shared wall, subsystem 4, with an aperture radius of 0. If there were an aperture in this wall ($r_a \neq 0$) SSINAP would compute the sound transmission through the hole as well as the mass-law sound transmission.

A.2.2.3 Power Sources

Sound and vibration enter the space station as power inputs to one or more subsystems. This information may be provided as a total power (in watts) or a power level (in dB relative to 1 pico watt) into a subsystem in each of nine octave bands centered from 31.5 to 8000 Hz or by selecting a source from a list of equipment. After identifying a subsystem for power input, the first thing the program asks is how many sources provide power to the subsystem. The program will evaluate the contribution of up to 10 separate power sources for each subsystem and sum their effects within each octave band. The statistical energy balance formulation requires only that some power enter the system from some source in every octave band.

Sets of power inputs from different sources may be entered in any order. As each input is entered, SSINAP computes the power level it produces in each of the nine octave bands. A running summation appears at the top of the screen of all previously entered sources for the current subsystem. Since the program ultimately forms a total power input to each subsystem in each octave band there is no record of the individual

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contributions of different sources. To save the individual source information the user should dump the screen to the printer each time SSINAP computes individual source levels.

SSINAP computes power input for four basic types of equipment, plus generic inputs. The screen dump in Figure A-5 shows the menu of choices SSINAP gives the user. At the top, SSINAP recalls the subsystem number and its type. Below this appears a row of running totals of power levels for the current subsystem. Just under this the program identifies the number of the power source for which data is being entered.

Each type of equipment requires its own set of input data, which depends on whether the subsystem is an air-space or panel. The following discussion describes each type of equipment, any limitations which apply, and the information required to describe it.

- HVAC Systems: If the subsystem is an air-space, SSINAP requests information on a duct diffuser. For panels, the user enters information concerning an HVAC compressor. Figures A-6 and A-7 show data entry for both cases.

- Electric Motors: Enter data for an AC or DC electric motor. The input format and information requested varies depending on whether the subsystem is an air-space or a panel (Figures A-8 and A-9).

- Fans: SSINAP computes the sound power generated in an air-space by eight types of fans, falling into two categories:

Centrifugal Types	Axial Types
- airfoil	- vane axial
- backward curve	- tube axial
- forward curve	- propeller
- radial	
- tubular	

The screen dump in Figure A-10 shows the required data for any type of fan.

Ventilation and equipment cooling fans usually introduce negligible structure-borne power to a panel; so, when the current subsystem is a structural element and the user selects a fan as a power source, the program gives a message noting that if structureborne noise is not negligible the power must be entered via the generic input.

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```
********************  ENTER THE SUBSYSTEM POWER MATRIX  ********************
********************  SUBSYSTEM  7 - RECTANGULAR SPACE  ********************

                          OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL            31.5    63    125   250   500  1000  2000  4000  8000
POWER LEVEL (dB)

****************************************************************************
********************  ENTERING LEVELS FOR SOURCE  1  ********************

        CHOOSE SOURCE TYPE FROM LIST BELOW:

              (1) DUCT DIFFUSOR OR COMPRESSOR OF HVAC SYSTEM
              (2) A.C. OR D.C. ELECTRIC MOTOR
              (3) VENTILATION OR EQUIPMENT COOLING FAN
              (4) CENTRIFUGAL PUMP
              (5) GENERIC POWER INPUT IN WATTS
              (6) GENERIC POWER LEVEL INPUT IN dB RE 1 pW

                        CHOICE:
```

Figure A-5. SSINAP Menu Choices.

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```
******************* ENTER THE SUBSYSTEM POWER MATRIX *******************
******************** SUBSYSTEM   7 - RECTANGULAR SPACE  ****************

                        OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL            31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)  88.7  95.7  102.7  109.7  115.7  119.7  123.8  120.8  117.7


***********************************************************************
******************** ENTERING LEVELS FOR SOURCE  1  *****************
************************** HVAC DUCT DIFFUSOR  ***********************


        CROSS-SECTIONAL AREA OF DUCT: 1.0          SQUARE METERS
        PRESSURE DROP ACROSS DIFFUSER: 5.0E3       PASCALS
                 AIR FLOW SPEED: 20.               METERS/SEC




                        OCTAVE BAND CENTER FREQUENCY (HZ)
                 31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)  88.7  95.7  102.7  109.7  115.7  119.7  123.8  120.8  117.7

        <<UPPER WINDOW SHOWS TOTAL POWER LEVEL FOR SOURCES 1 -  1 >>
              <<            PRESS ENTER TO CONTINUE          >>
```

Figure A-6.   Data Entry for the Computation of Acoustical Power
Into an Air-Space From an HVAC Duct Diffuser.

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```
******************** ENTER THE SUBSYSTEM POWER MATRIX ********************
******************** SUBSYSTEM  5 - RECTANGULAR PANEL  ********************

                        OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL              31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)   67.3   68.2   65.3   57.3   49.3   44.2   34.2   25.2   22.2


******************************************************************************
******************** ENTERING LEVELS FOR SOURCE  1  ********************
************************** HVAC COMPRESSOR  ************************



        RATED POWER OF COMPRESSOR DRIVE MOTOR:   1000          WATTS

            IS THE SOURCE VIBRATION ISOLATED?   Y


                        OCTAVE BAND CENTER FREQUENCY (HZ)
                   31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)   67.3   68.2   65.3   57.3   49.3   44.2   34.2   25.2   22.2

        <<UPPER WINDOW SHOWS TOTAL POWER LEVEL FOR SOURCES 1 -  1 >>
             <<              PRESS ENTER TO CONTINUE          >>
```

Figure A-7. Data Entry for the Computation of Vibrational Power
Into a Panel From an HVAC Compressor.

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```
******************* ENTER THE SUBSYSTEM POWER MATRIX *******************
******************* SUBSYSTEM 13 - RECTANGULAR SPACE *******************

                         OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL             31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)  -3.3   -3.3   1.7    6.7   11.7   11.7   10.7    4.7   -2.3

*************************************************************************
******************** ENTERING LEVELS FOR SOURCE  1 ********************
******************** A.C. OR D.C. ELECTRIC MOTOR ********************

          (1) A.C. ELECTRIC MOTOR
          (2) D.C. ELECTRIC MOTOR

                         CHOICE: 2

          RATED POWER OF MOTOR: 500          WATTS
          RATED SPEED OF MOTOR: 1200         RPM

                         OCTAVE BAND CENTER FREQUENCY (HZ)
                  31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)  -3.3   -3.3   1.7    6.7   11.7   11.7   10.7    4.7   -2.3

      <<UPPER WINDOW SHOWS TOTAL POWER LEVEL FOR SOURCES 1 -  1 >>
            <<              PRESS ENTER TO CONTINUE            >>
```

Figure A-8.   Data Entry for the Computation of Acoustical Power
Into an Air-Space From an Electric Motor.

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LABORATORIES

```
********************  ENTER THE SUBSYSTEM POWER MATRIX  ********************
********************  SUBSYSTEM   5 - RECTANGULAR PANEL  ********************

                       OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL              31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)   77.5   72.9   68.3   60.9   53.6   47.4   39.0   32.2   27.1


**********************************************************************************
********************  ENTERING LEVELS FOR SOURCE  3  ********************
********************  A.C. OR D.C. ELECTRIC MOTOR  ********************

          (1) A.C. ELECTRIC MOTOR
          (2) D.C. ELECTRIC MOTOR

                    CHOICE: 2

          IS THE SOURCE VIBRATION ISOLATED?   Y


                       OCTAVE BAND CENTER FREQUENCY (HZ)
                   31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)   59.0   53.9   49.0   46.0   42.0   35.9   24.9   19.9   14.9

       <<UPPER WINDOW SHOWS TOTAL POWER LEVEL FOR SOURCES 1 -  3 >>
            <<              PRESS ENTER TO CONTINUE          >>
```

Figure A-9. Data Entry for the Computation of Vibrational Energy
Into a Panel From an Electric Motor.

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```
******************** ENTER THE SUBSYSTEM POWER MATRIX ********************
******************** SUBSYSTEM  7 - RECTANGULAR SPACE  ********************

                        OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL             31.5     63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)  131.3  128.3  132.3  126.4  125.8  124.9  126.1  123.5  118.3


*************************************************************************
******************** ENTERING LEVELS FOR SOURCE  2  ********************
*************************** PROPELLER AXIAL FAN  ***************************




        VOLUME FLOW THROUGH FAN: 20          CUBIC METERS/SEC
     STATIC PRESSURE ACROSS FAN: 1.E4        PASCALS
           RATED SPEED OF FAN: 1800          RPM
        NUMBER OF BLADES ON FAN: 5


                     OCTAVE BAND CENTER FREQUENCY (HZ)
                  31.5     63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)  131.3  128.3  132.3  126.3  125.3  123.3  122.3  120.3  109.3

     <<UPPER WINDOW SHOWS TOTAL POWER LEVEL FOR SOURCES 1 -  2 >>
           <<              PRESS ENTER TO CONTINUE          >>
```

Figure A-10. Data Entry for the Computation of Acoustical Power
Into an Air-Space From a Fan.

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- Centrifigal Pump: The information which the program needs to determine the power contributed by a centrifugal pump depends on the type of subsystem the power enters. Samples of input for both air-spaces and panels are given in Figures A-11 and A-12. For panels, a moderate amount of vibration isolation is assumed when such isolation is present.

- Generic Power Input: When the user knows the acoustic or vibrational power or power level entering the subsystem from a source, these values can be entered directly using one of the two generic input options. The data table format is the same whether entering power or level. SSINAP computes the octave band powers in watts, if the user enters levels, or the octave band power levels in dB re 1 pico watt, if the user enters powers. All values appear on the screen (see Figure A-13). The subsystem type does not affect the input of generic data.

A.2.3   Statistical Energy Analysis

After the space station has been completely described, the user may perform a statistical energy analysis of the system. SSINAP performs the analysis for each of nine octave bands centered at 31.5, 63, 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. The results consist of levels in each octave band for each subsystem. If the subsystem is a structural element, the program gives the vibration velocity level relative to 10 nano-meters per second. For air-spaces, the SEA computes sound pressure level relative to 20 micro-Pascals.

At the end of the calculation the program asks if the results should be printed. Also, the SEA results will be included in any printout of the subsystem data set as long as the space station has not been modified since the calculation was performed. Writing the subsystem data set to a disk file preserves these results so they can be used as input for subsequent STI calculations. When results are stored on disk they appear as pressure-squared or vibration-velocity-squared rather than as levels, thus preserving accuracy.

A.2.4   Speech Transmission Index

When a subsystem data set and the associated SEA calculated background noise levels are available, the average speech transmission index (STI) can be computed for any air-space. This index represents the effect of the sound transmission system on speech intelligibility. For an air-space the sound transmission system consists of the room

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```
******************** ENTER THE SUBSYSTEM POWER MATRIX ********************
******************** SUBSYSTEM  7 - RECTANGULAR SPACE  ********************

                         OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL             31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)  131.3  128.3  132.3  126.4  125.8  124.9  126.1  123.5  118.3

*************************************************************************
********************* ENTERING LEVELS FOR SOURCE  3 *********************
*************************** CENTRIFUGAL PUMP  ***************************



          RATED POWER OF PUMP DRIVE MOTOR:  2000          WATTS
                     RATED SPEED OF PUMP:  240           RPM



                       OCTAVE BAND CENTER FREQUENCY (HZ)
                  31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB)  80.0   80.0   81.0   81.0   82.0   84.0   81.0   78.0   73.0

          <<UPPER WINDOW SHOWS TOTAL POWER LEVEL FOR SOURCES 1 - 3 >>
                <<            PRESS ENTER TO CONTINUE            >>
```

Figure A-11.   Data Entry for the Computation of Acoustical Power
               Into an Air-Space From a Centrifugal Pump.

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```
******************** ENTER THE SUBSYSTEM POWER MATRIX ********************
******************** SUBSYSTEM  5 - RECTANGULAR PANEL ********************

                        OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL            31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB) 77.5   72.9  68.6   61.1   54.5  48.5   39.8   34.3   28.5

*****************************************************************************
********************** ENTERING LEVELS FOR SOURCE  4 **********************
************************************** CENTRIFUGAL PUMP **********************



          RATED POWER OF PUMP DRIVE MOTOR:  1500         WATTS

             IS THE SOURCE VIBRATION ISOLATED?  N


                        OCTAVE BAND CENTER FREQUENCY (HZ)
                 31.5    63    125    250    500   1000   2000   4000   8000
POWER LEVEL (dB) 48.1   50.0  57.1   49.1   47.1  42.0   32.0   30.0   23.0

       <<UPPER WINDOW SHOWS TOTAL POWER LEVEL FOR SOURCES 1 -  4 >>
            <<              PRESS ENTER TO CONTINUE           >>
```

Figure A-12. Data Entry for the Computation of Vibrational Power
Into a Panel From a Centrifugal Pump.

```
******************** ENTER THE SUBSYSTEM POWER MATRIX ********************
******************** SUBSYSTEM   7 - RECTANGULAR SPACE  ********************

                          OCTAVE BAND CENTER FREQUENCY (HZ)
TOTAL              31.5    63    125    250  -  500   1000   2000   4000   8000
POWER LEVEL (dB)  131.6  129.0  132.9  128.4  128.4  126.1  129.3  127.5  124.7

*****************************************************************************
******************** ENTERING LEVELS FOR SOURCE   4  ********************

                 CENTER                 POWER
                FREQUENCY     POWER      LEVEL
                  (HZ)       (WATTS)   (dB re 1pW)
                  31.5      9.000E-01    119.5
                   63       1.100E+00    120.4
                  125       2.300E+00    123.6
                  250       2.600E+00    124.1
                  500       3.200E+00    125.1
                 1000       1.000E+00    120.0
                 2000       4.500E+00    126.5
                 4000       3.300E+00    125.2
                 8000       2.300E+00    123.6

        <<UPPER WINDOW SHOWS TOTAL POWER LEVEL FOR SOURCES 1 -  4 >>
             <<          PRESS ENTER TO CONTINUE           >>
```

Figure A-13. Entry of Generic Acoustical or Vibrational Octave Band
Powers or Power Levels.

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geometry and the background noise levels and the reverberation times in four octave bands centered at 500, 1000, 2000, and 4000 Hz. An index near 100 indicates excellent intelligibility while a value of 40 or lower means poor intelligibility.

After the user chooses Main Menu Option (7), the STI module, an STI menu appears offering the following choices:

(1) Enter STI data

(2) Modify STI data

(3) Compute STI

(4) Print STI variables and results

(5) Return to Main Menu

The user must execute Option (1) before progressing to other steps, except for exiting. The program prompts the user for all the necessary information. Some variables have defaults which appear on the screen and can be accepted or overwritten. When modifying data the user keeps the current value by pressing "Return".

The screen dump in Figure A-14 shows the input variables (underlined) which the STI module needs to compute the index.

Once the user chooses a subsystem, the program determines the air-space surface area and absorption coefficients and fetches the background noise levels in the four octave bands. The user enters the speaker sound level in each of these bands. If the user later changes the subsystem choice the background levels will be corrected and the user reenters the speaker levels.

The directivity factor of the speaker on axis is usually taken as 6 for a moderately directive loudspeaker with uniform coverage over 90 degrees. A person speaking is usually assigned a directivity of 2 and this is the program default. The listener directivity factor is usually taken as 1.5 if the listener is facing the sound source. Setting this factor to 1.0 gives a more conservative estimate for a listener facing any direction.

The STI calculation depends on the age of the listener population. The confidence level determines for what percentage of that population the predicted STI will be valid.

```
********************************************************************
*                          DATA INPUT                             *
********************************************************************

     (1)              NUMBER OF TARGET SUBSYSTEM: 13

              INPUT SOUND POWER LEVELS (dB re 20 uPa)
              *****************************************
      OCTAVE FREQ          BACKGROUND NOISE          SPEAKER

          500            (2)  107.7        (6)  105.0  <<
         1000            (3)  103.1        (7)  105.0  <<
         2000            (4)   98.8        (8)  100.0  <<
         4000            (5)   97.6        (9)  100.0  <<


   (10)        SPEAKER-TO-LISTENER DISTANCE (m):     2.0
   (11)                     CONFIDENCE LEVEL (%):   95.0
   (12)             SPEAKER DIRECTIVITY FACTOR:      2.0
   (13)            LISTENER DIRECTIVITY FACTOR:      1.5
   (14)                           LISTENER AGE:     35.0

   <<     ENTER THE NUMBER OF THE ITEM TO BE CHANGED     >>
   <<                ("ENTER" FOR NO CHANGES)            >>
```

Figure A-14. Input Variables for STI Calculation.

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Output for the STI module (Figure A-15) consists of the calculated value of STI plus a listing of all input variables used and computed signal-to-noise differences. When the STI calculation finishes, the program offers to print the output. The additional STI menu option to print can also be exercised any time after computing the STI but before exiting the module. The sample background levels presented in Figures 14 and 15 were generated using the data file, NEW3A.DAT, given in the appendix.

The STI values computed from the program can be used, if desired, to estimate various measures of speech intelligibility. However, a design target of about 45 for STI will generally ensure very good speech communication results.

A.3 PROGRAMMING REFERENCE GUIDE

Since SSINAP has been designed to be user-friendly, every effort has been made to keep the source code programmer-friendly as well. The FORTRAN source files provided on the installation disk are fully annotated throughout and contain introductory documentation. This guide provides a quick reference to important programming features.

Section A.3.1 describes the computing system requirements and a suggested linking procedure. The next two sections, A.3.2 and A.3.3, discuss the functions of the main program and the 34 subroutines and their relationships. Section A.3.4 provides a list of the variables which pass between program segments in common blocks. In addition to this list each subroutine source file contains documentation of all variables input to, output from, or used within that subroutine.

Any questions or comments should be addressed to Eric Stusnick, Wyle Laboratories, 2001 Jefferson Davis Highway, Suite 701, Arlington, Virginia 22202, 703/892-6700.

A.3.1   System Requirements and Procedures

A.3.1.1   Computing System Requirements

SSINAP has been developed on an IBM PC using Microsoft FORTRAN Version 3.3 running under PC DOS, Version 2.1. The program should also run in similar MS DOS environments, such as the Tandy 2000 and DEC Rainbow microcomputers. An ANSI.SYS device driver must be installed in the host operating system. To accomplish this include the command:

DEVICE = ANSI.SYS

in the CONFIG.SYS file and ensure that the ANSI.SYS file is included on the system diskette when the computer boots. The executable code is approximately 145K bytes.

```
              FILE NAME - NEW3A.DAT


TEST3: CASE A - SOUND TRANSMISSION BETWEEN 2 IDENTICAL CUBES


    SPEECH TRANSMISSION INDEX RESULTS FOR SUBSYSTEM 13


                     SURFACE AREA:     6.0 square meters
         SPEAKER-LISTENER DISTANCE:    2.0 meters
              SPEAKER DIRECTIVITY:     2.0
             LISTENER DIRECTIVITY:     1.5
                 CONFIDENCE LEVEL:     95.0 %
                    LISTENER AGE:      35.0 years

                         OCTAVE BAND CENTER FREQUENCY
                         500     1000    2000     4000
    AVG. ABSORBTION COEFF.    .1      .1       .1       .1
    BACKGROUND NOISE (dB)   107.7   103.1    98.8     97.6
    SPEAKER SIGNAL (dB)     105.0   105.0   100.0    100.0
    SIGNAL-TO-NOISE (dB)     -2.7     1.9     1.2      2.4

        AVERAGE SPEECH TRANSMISSION INDEX:    25.8
```
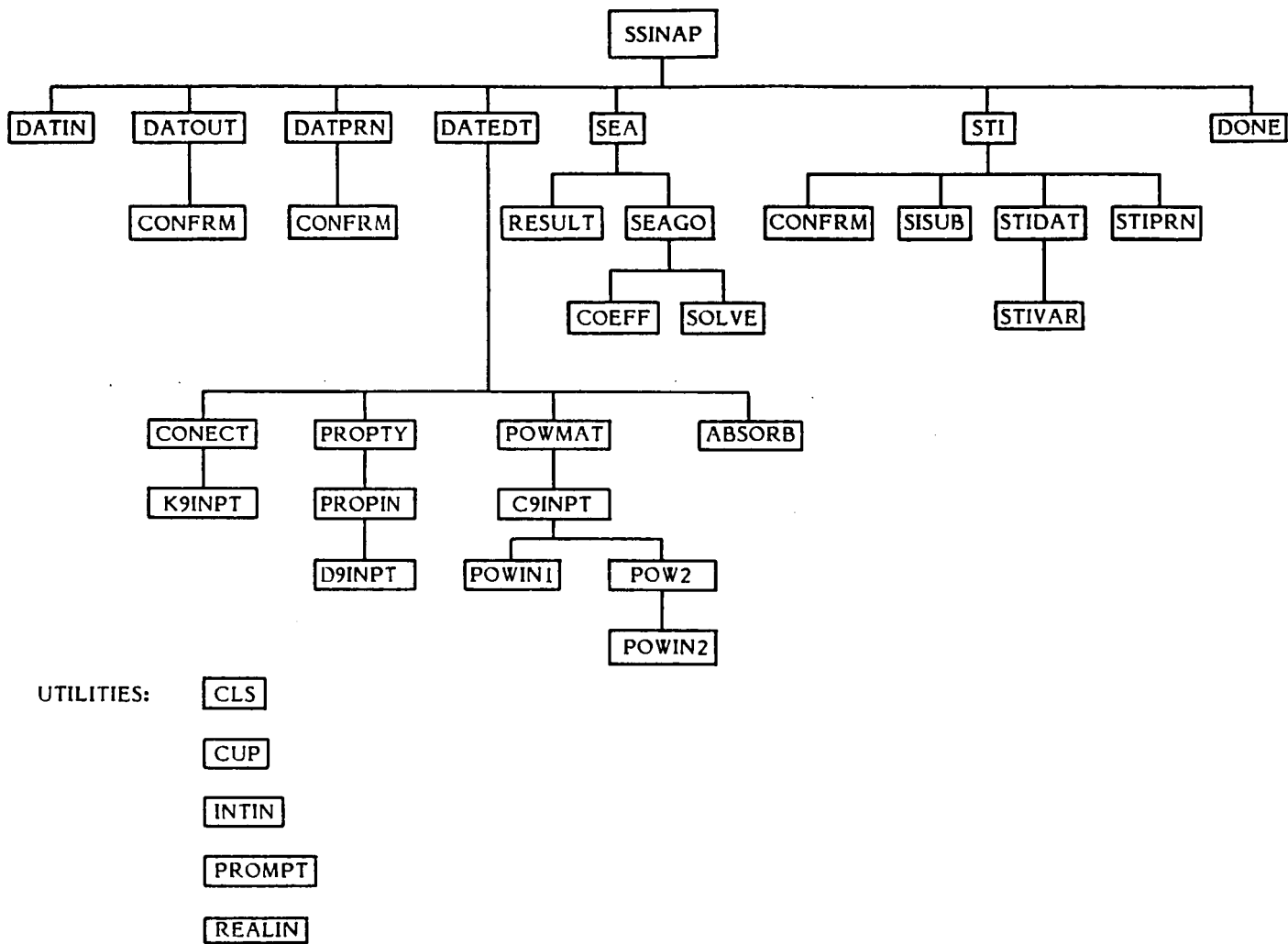
Figure A-15. Output for the STI Module.

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Figure A-16. SSINAP Block Diagram.

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Only standard FORTRAN statements are used and the program does not include any proprietary or assembly language routines.

A.3.1.2 Linking Procedure

Wyle Laboratories has provided NASA with two diskettes: one containing an executable file, SSINAP.EXE, and the other containing the FORTRAN source code for all program modules. If the user chooses to recompile the source code, it can be relinked using the link response file SSINAP.LNK, contained on the source code diskette.

A.3.2 Block Diagram

SSINAP consists of a main module and 32 subroutines, all of which are described in the Subroutine Directory which follows. Figure A-16 illustrates the block diagram of SSINAP.

A.3.3 Subroutine Directory

ABSORB   Function: Interactive input of absorption coefficient matrix.

              Called By: DATEDT

              Subroutines Called: CLS, CUP, INTIN, REALIN

C9INPT   Function: Interactive input of source power values for a single subsystem

              Called By: POWMAT

              Subroutines Called: CLS, CUP, INTIN, POWIN1, POW2

CLS   Function: Erases the screen display and positions the cursor in the upper left-hand corner (home).

              Called By: ABSORB, C9INPT, CONECT, DONE, POWMAT, PROPIN, PROPTY, RESULT, SEA, SSINAP, STI, STIDAT, STIPRN

              Subroutines Called: CHAR (intrinsic)

COEFF   Function: Generates the coefficients for the system of power balance equations used in the statistical energy analysis of the space station.

              Called By: SEAGO

              Subroutines Called: None except for functions internal to COEFF.

CONECT   Function: Interactive input of subsystem connectivity matrix.

              Called By: DATEDT

              Subroutines Called: CLS, CUP, INTIN, K9INPT

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CONFRM Function: Verifies availability of SEA output, computes levels from pressure-squared and vibration-velocity-squared if needed.

Called By: DATPRN, STI

Subroutines Called: None

CUP Function: Moves the screen cursor to a specified position

Called By: ABSORB, C9INPT, CONECT, D9INPT, DATIN, DATOUT, DATPRN, DONE, INTIN, K9INPT, POW2, POWIN1, POWIN2, POWMAT, PROPIN, PROPTY, REALIN, RESULT, SEA, SSINAP, STI, STIDAT, STIPRN, STIVAR

Subroutines Called: CHAR (intrinsic)

D9INPT Function: Interactive input of individual elements of the subsystem property matrix, D9.

Called By: PROPIN

Subroutines Called: CUP, INTIN, REALIN

DATEDT Function: Create a new subsystem data set in memory and control interactive data input. Control data set modification.

Called By: SSINAP

Subroutines Called: ABSORB, CONECT, CUP, INTIN, POWMAT, PROPTY

DATIN Function: Read a subsystem data set from disk to memory

Called By: SSINAP

Subroutines Called: CUP

DATOUT Function: Write a subsystem data set from memory to disk

Called By: SSINAP

Subroutines Called: CUP

DATPRN Function: Print a data set currently in memory

Called By: SSINAP

Subroutines Called: CUP, CONFRM

DONE Function: Checks that current subsystem data set has been saved or is no longer needed and returns to DOS.

Called By: SSINAP

Subroutines Called: CLS, CUP

INTIN Function: Interactive input of integer variable with range checking and error trapping

Called By: C9INPT, CONECT, D9INPT, DATEDT, K9INPT, POWIN1, POWMAT, PROPIN, PROPTY, SSINAP, STIDAT, STIVAR

Subroutines Called: CUP, ICHAR (Intrinsic)

K9INPT Function: Interactive input of individual elements of connectivity matrix, K9.

Called By: CONECT

Subroutines Called: CUP, INTIN

POW2 Function: Controls input of generic power values

Called By: C9INPT

Subroutines Called: CUP, POWIN2, REALIN

POWIN1 Function: Interactive input of equipment power source variables and calculation of power input to subsystem by these sources.

Called By: C9INPT

Subroutines Called: CUP, INTIN, REALIN

POWIN2 Function: Interactive input of generic power values for a single octave band.

Called By: POW2

Subroutines Called: CUP, REALIN

POWMAT Function: Control input of subsystem power matrix, C9

Called By: DATEDT

Subroutines Called: CLS, CUP, INTIN, C9INPT

PROMPT Function: Block data initialization.

PROPIN Function: Control input of properties for one subsystem

Called By: PROPTY

Subroutines Called: CLS, CUP, D9INPT, INTIN

PROPTY Function: Control input of subsystem property matrix, D9

Called By: DATEDT

Subroutines Called: CLS, CUP, INTIN, PROPIN

REALIN Function: Interactive input of a single real value with range checking and error trapping

Called By: ABSORB, D9INPT, POW2, POWIN1, POWIN2, STIVAR

Subroutines Called: CUP, ICHAR (intrinsic)

RESULT Function: Write results of SEA calculation to the screen and print if desired.

Called By: SEA

Subroutines Called: CLS, CUP

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SEA   Function: Control statistical energy analysis of space station and output of results.

Called By: SSINAP

Subroutines Called: CLS, CUP, RESULT, SEAGO

SEAGO   Function: Perform statistical energy analysis (SEA)

Called By: SEA

Subroutines Called: COEFF, SOLVE

SISUB   Function: Calculate speech transmission index (STI)

Called By: STI

Subroutines Called: None

SOLVE   Function: Solve system of N simultaneous equations using Gauss-Jordan Reduction with a maximum pivot strategy.

Called By: SEAGO

Subroutines Called: None

SSINAP   Function: MAIN PROGRAM

Subroutines Called: CLS, CUP, DATEDT, DATIN, DATOUT, DATPRN, DONE, INTIN, SEA, STI

STI   Function: Control input of variables, calculation of speech transmission index (STI), and output

Called By: SSINAP

Subroutines Called: CLS, CONFRM, CUP, REVERB, SISUB, STIDAT, STIPRN

STIDAT   Function: Prompt user for input data needed for STI calculation

Called By: STI

Subroutines Called: CLS, CUP

STIPRN   Function: Writes results of the STI calculation to the screen and to a line printer or output file.

Called By: STI

Subroutines Called: CLS, CUP

STIVAR   Function: Interactive input of single STI variable

Called By: STIDAT

Subroutines Called: CUP, INTIN, REALIN

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A.3.4 Variable List

Common Block Name	Variable (i, j)	Function
/DATA/	A9 (4, 9)	Absorption coefficients: i = table number j = octave band Center frequencies are 31.5, 63.0, 125, 250, 500, 1000, 2000, 4000, 8000 Hz
	C or CC	Data set title, 60 characters
	C9 (20, 9)	Input Power Source Matrix; holds powers entering subsystems i = subsystem number j = octave band
	D9 (20, 7)	Subsystem Property Matrix; holds material properties and dimensions of subsystems. i = subsystem number j = property index
	K9 (20, 20)	Connectivity Matrix; holds subsystem type and connection type identifiers i = "from" subsystem $\Big\}$ $i \neq j$ j = "to" subsystem
	N	Number of subsystems used to define the space station, up to 20
	N8	Number of absorption tables in A9, up to 4.
/ID/	F	Current octave band center frequency
	K8	Pointer to octave band of which F is center frequency
	OM, OMEGA	$2*PI*F$
/PRMPT/	IDELAY	Integer counter used to time pauses in program.
	PRMPT(5)	Character strings of frequently used program prompts and messages
/SOLN/	AER (20)	Absolute error vector, computed by substituting solutions, $p**2$ or $v**2$, back into power balance equations i = subsystem number

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Common Block Name	Variable (i,j)	Function
/SOLN/ (Cont'd)	C (20, 20)	Coefficient matrix for power balance equations used in statistical energy analysis i, j = subsystem numbers
	PV (20, 9)	Matrix of solution vectors, holds p**2 or v**2 values i = subsystem number j = octave band
	T (20, 21)	Augmented coefficient matrix holds C (20, 20) plus appropriate column of C9 matrix in last column
	X (20, 9)	Matrix of solution vectors, comparable to PV but holding levels
/SUB1/	ABAR (4)	Average absorption coefficients for air-space in four octave bands, taken from A9.
	AGE	Age of target population for STI calculation in years
	AREA	Surface area of air-space in square meters, taken from D9.
	ID	Number of target air-space subsystem for STI calculation
	IGOT	Logical flag tells if STI input data is available
	P	Percent confidence interval for target population in STI calculation
	QL	Directivity factor of listener in STI calculation
	QT	Directivity factor of speaker
	RS	Speaker-to-listener distance in meters
	S (4)	Speaker signal sound level in four octave bands centered at 500, 1000, 2000, and 4000 Hz
	UGOT	Logical flag indicates if STI results are available
	WEGOT	Logical flag tells if SEA results have been computed, making background noise levels available for STI calculation

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A.4 SAMPLE OF PROGRAM INPUT AND OUTPUT

A.4.1 Sample Input File NEW3A.DAT

```
TEST3: CASE A - SOUND TRANSMISSION BETWEEN 2 IDENTICAL CUBES
13 SUBSYSTEMS
 1 ABSORPTION TABLE

SUBSYSTEM CONNECTION MATRIX (K9)
 I/J 1   2   3   4   5   6   7   8   9  10  11  12  13
  1  -1   3   0   1   3   3   4   2   0   0   0   0   0
  2   3  -1   3   0   3   3   4   0   0   0   0   0   0
  3   0   3  -1   1   3   3   4   0   0   2   0   0   0
  4   1   0   1  -1   1   1   4   1   0   1   1   1   4
  5   3   3   3   1  -1   0   4   0   0   0   2   0   0
  6   3   3   3   1   0  -1   4   0   0   0   0   2   0
  7   5   5   5   5   5   5  -2   0   0   0   0   0   9
  8   2   0   0   1   0   0   0  -1   3   0   3   3   4
  9   0   0   0   0   0   0   0   3  -1   3   3   3   4
 10   0   0   2   1   0   0   0   0   3  -1   3   3   4
 11   0   0   0   1   2   0   0   3   3   3  -1   0   4
 12   0   0   0   1   0   2   0   3   3   3   0  -1   4
 13   0   0   0   5   0   0   9   5   5   5   5   5  -2
```

```
SUBSYSTEM PROPERTY MATRIX (D9) -
        : 1:THICKNESS:     LENGTH:    WIDTH: WAVE SPD:   DENSITY:LOSS FCTR:APTUR RAD:
        : 2:    VOLUME:SURF AREA: CHAR IMP:SOUND SPD:        :          : ABS PNTR:
   TYPE 3:    LENGTH:    RADIUS: CHAR IMP:SOUND SPD:        :          : ABS PNTR:
        : 4:THICKNESS:    LENGTH:   RADIUS: WAVE SPD:   DENSITY:LOSS FCTR:APTUR RAD:
        : 5:THICKNESS:          :   RADIUS: WAVE SPD:   DENSITY:LOSS FCTR:APTUR RAD:
    I TYPE
 1   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
 2   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
 3   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
 4   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
 5   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
 6   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
 7   2  1.00E+00   6.00E+00   4.15E+02   3.43E+02   .00E+00    .00E+00    1.00E+00
 8   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
 9   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
10   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
11   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
12   1  1.59E-03   1.00E+00   1.00E+00   6.30E+03   2.70E+03   1.00E-02   .00E+00
13   2  1.00E+00   6.00E+00   4.15E+02   3.43E+02   .00E+00    .00E+00    1.00E+00
```

```
SUBSYSTEM POWER MATRIX (C9):
  I     31.5        63        125        250        500
  1  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  2  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  3  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  4  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  5  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  6  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  7  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00
  8  1.000E-37  1.000E-37  1.000E-37  1.000E-37 .1.000E-37
  9  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
 10  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
 11  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
 12  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37
 13  1.000E-37  1.000E-37  1.000E-37  1.000E-37  1.000E-37


  I     1000       2000       4000       8000
  1  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  2  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  3  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  4  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  5  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  6  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  7  1.000E+00  1.000E+00  1.000E+00  1.000E+00
  8  1.000E-37  1.000E-37  1.000E-37  1.000E-37
  9  1.000E-37  1.000E-37  1.000E-37  1.000E-37
 10  1.000E-37  1.000E-37  1.000E-37  1.000E-37
 11  1.000E-37  1.000E-37  1.000E-37  1.000E-37
 12  1.000E-37  1.000E-37  1.000E-37  1.000E-37
 13  1.000E-37  1.000E-37  1.000E-37  1.000E-37
```

```
ABSORPTION COEFFICIENT MATRIX (A9):
  I  31.5    63    125   250   500  1000  2000  4000  8000
  1  .050   .050  .050  .050  .050  .050  .050  .050  .050
```

A33

A.4.2   Sample Printout

FILE NAME - C:NEW3A.DAT

TEST3: CASE A - SOUND TRANSMISSION BETWEEN 2 IDENTICAL CUBES

13 SUBSYSTEMS

1 ABSORPTION TABLE

SUBSYSTEM CONNECTION MATRIX (K9)

```
I/J  1    2    3    4    5    6    7    8    9   10   11   12   13
 1  -1    3    0    1    3    3    4    2    0    0    0    0    0
 2   3   -1    3    0    3    3    4    0    0    0    0    0    0
 3   0    3   -1    1    3    3    4    0    0    2    0    0    0
 4   1    0    1   -1    1    1    4    1    0    1    1    1    4
 5   3    3    3    1   -1    0    4    0    0    0    2    0    0
 6   3    3    3    1    0   -1    4    0    0    0    0    2    0
 7   5    5    5    5    5    5   -2    0    0    0    0    0    9
 8   2    0    0    1    0    0    0   -1    3    0    3    3    4
 9   0    0    0    0    0    0    0    3   -1    3    3    3    4
10   0    0    2    1    0    0    0    0    3   -1    3    3    4
11   0    0    0    1    2    0    0    3    3    3   -1    0    4
12   0    0    0    1    0    2    0    3    3    3    0   -1    4
13   0    0    0    5    0    0    9    5    5    5    5    5   -2
```

A34

WYLE
LABORATORIES

TEST3: CASE A - SOUND TRANSMISSION BETWEEN 2 IDENTICAL CUBES

SUBSYSTEM PROPERTY MATRIX (D9)

		1 THICKNESS	LENGTH	WIDTH	WAVE SPD	DENSITY	LOSS FCTR	APTUR RAD
		2 VOLUME	SURF AREA	CHAR IMP	SOUND SPD			ABS PNTR
TYPE		3 LENGTH	RADIUS	CHAR IMP	SOUND SPD			ABS PNTR
		4 THICKNESS	LENGTH	RADIUS	WAVE SPD	DENSITY	LOSS FCTR	APTUR RAD
		5 THICKNESS		RADIUS	WAVE SPD	DENSITY	LOSS FCTR	APTUR RAD

I	TYPE							
1	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
2	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
3	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
4	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
5	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
6	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
7	2	1.00E+00	6.00E+00	4.15E+02	3.43E+02	.00E+00	.00E+00	1.00E+00
8	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
9	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
10	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
11	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
12	1	1.59E-03	1.00E+00	1.00E+00	6.30E+03	2.70E+03	1.00E-02	.00E+00
13	2	1.00E+00	6.00E+00	4.15E+02	3.43E+02	.00E+00	.00E+00	1.00E+00

SUBSYSTEM SOUND POWER LEVEL MATRIX (C9)

I	31.5	63	125	250	500	1000	2000	4000	8000
1	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
2	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
3	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
4	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
5	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
6	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
7	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0
8	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
9	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
10	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
11	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
12	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0
13	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0	-250.0

ABSORPTION COEFFICIENT MATRIX (A9)

I	31.5	63	125	250	500	1000	2000	4000	8000
1	.050	.050	.050	.050	.050	.050	.050	.050	.050

WYLE
LABORATORIES

TEST3: CASE A - SOUND TRANSMISSION BETWEEN 2 IDENTICAL CUBES

SOUND PRESSURE LEVELS (dB: 20 uPa) & VIBRATION VELOCITY LEVELS (dB: 10 nm/s)
* *

OCTAVE BAND CENTER FREQUENCY

ID	31.50	63.00	125.0	250.0	500.0	1000.	2000.	4000.	8000.	(Hz)
1 (V)	139.69	136.41	132.97	129.09	124.55	119.14	112.94	106.36	109.85	
2 (V)	139.71	136.43	132.99	129.11	124.57	119.16	112.96	106.38	109.87	
3 (V)	139.69	136.41	132.97	129.09	124.55	119.14	112.94	106.36	109.85	
4 (V)	139.65	136.36	132.92	129.04	124.50	119.09	112.89	106.31	109.77	
5 (V)	139.69	136.41	132.97	129.09	124.55	119.14	112.94	106.36	109.85	
6 (V)	139.69	136.41	132.97	129.09	124.55	119.14	112.94	106.36	109.85	
7 (P)	122.14	123.72	125.44	127.24	128.88	130.08	130.76	131.07	129.98	
8 (V)	139.56	136.27	132.82	128.94	124.40	118.99	112.79	106.21	109.65	
9 (V)	139.54	136.25	132.80	128.92	124.38	118.97	112.77	106.19	109.62	
10 (V)	139.56	136.27	132.82	128.94	124.40	118.99	112.79	106.21	109.65	
11 (V)	139.56	136.27	132.82	128.94	124.40	118.99	112.79	106.21	109.65	
12 (V)	139.56	136.27	132.82	128.94	124.40	118.99	112.79	106.21	109.65	
13 (P)	114.43	114.24	113.75	113.00	111.52	108.81	104.88	100.40	117.05	

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15. Supplementary Notes

Langley Technical Monitor: Dr. Clemens A. Powell, Jr.
Final Report

16. Abstract

This report provides documentation for a microcomputer program which was developed to evaluate the effect of the vibroacoustic environment on speech communication inside a space station. The program, entitled "Space Station Interior Noise Analysis Program" (SSINAP), combines a Statistical Energy Analysis (SEA) prediction of sound and vibration levels within the space station with a speech intelligibility model based on the Modulation Transfer Function and the Speech Transmission Index (MTF/STI).

The SEA model provides an effective analysis tool for predicting the acoustic environment based on proposed space station design. The MTF/STI model provides a method for evaluating speech communication in the relatively reverberant and potentially noisy environments that are likely to occur in space stations. The combination of these two models provides a powerful analysis tool for optimizing the acoustic design of space stations from the point of view of speech communications.

The main body of this report presents the mathematical algorithms used in SSINAP to implement the SEA and MTF/STI models. An appendix provides an explanation of the operation of the program along with details of the program structure and code.

17. Key Words (Suggested by Authors(s)) Space Station Noise Space Station Vibration Statistical Energy Analysis Modulation Transfer Function Speech Transmission Index	18. Distribution Statement Unclassified – Unlimited Subject Category 71	
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