Chapter II.3

Coupled Rooms

II.3.1 Steady-state Conditions with an Open Coupling Area

The statistical analysis of a room, as developed in Chapter II. 1, is not applicable for rooms which, although they may comprise a single air volume, are nevertheless subdivided architecturally into a number of smaller subspaces. This happens, for instance, in churches where the high central nave is abutted by lower side aisles or by side chapels; also, in older court theaters there are often many rather deep boxes.

As a simple example, Fig. 3.1 shows the case where a large lecture hall with volume V_1 is coupled to a low, acoustically damped entry room of volume V_2 in such a way that the already small coupling area is further reduced by a deep beam, to S_{12}.

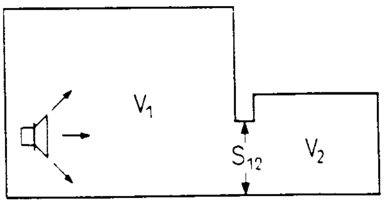

Fig. 3.1. Sketch of a section through two coupled rooms.

In this case, it cannot be expected that the sound power P_1 emitted in the lecture hall will be equally distributed throughout both rooms. In fact, experience shows that there is a remarkable decrease in loudness as one passes from the lecture hall into the entry room.

It is one of the advantages of statistical room acoustics that, even in such cases, the main acoustical features can be exhibited by distinguishing between the mean energy densities, E_1 and E_2, each equally distributed in the respective partial rooms. This analysis replaces the actual gradual transition between E_1 and E_2 with a step-wise change in energy density at the coupling surface S_{12}.

If we denote by A_{10} the equivalent absorption area of room 1 (including all surfaces and absorptive objects except S_{12}) and by A_{20} the corresponding quantity for room 2, we get (according to Section II.1.4) the respective amounts of sound power actually absorbed in the two rooms (assuming, as usual, diffuse sound fields):

$$(A_{10}E_1c/4) \quad \text{and} \quad (A_{20}E_2c/4)$$

In addition, the power transferred from room 1 to room 2 is:

$$(S_{12}E_1c/4)$$

and that from room 2 to room 1 is:

$$(S_{12}E_2c/4).$$

Thus, we can write power balances for the two rooms as follows:

$$P_1-(c/4)A_{10}E_1-(c/4)S_{12}E_1+(c/4)S_{12}E_2=0 \tag{3.1}$$

$$(c/4)S_{12}E_1-(c/4)A_{20}E_2-(c/4)S_{12}E_2=0 \tag{3.2}$$

By introducing

$$A_{11}=A_{10}+S_{12}$$

and

$$A_{22}=A_{20}+S_{12} \tag{3.3}$$

(which means that we include, as part of the total equivalent absorption areas of the rooms, the coupling area S_{12} with the absorption coefficient of unity) we may write eqns. (3.1) and (3.2) in the usual form for coupling problems:

$$\frac{4P_1}{c}=A_{11}E_1-S_{12}E_2 \tag{3.4}$$

$$0=-S_{12}E_1+A_{22}E_2 \tag{3.5}$$

Solving these coupling equations leads to the energy density in room 1, containing the source:

$$E_1=\frac{4P_1/c}{A_{11}-S_{12}^2/A_{22}} \tag{3.6}$$

If we had treated the two rooms as a single acoustical space we would have found the following expression for the common mean energy density:

$$E = \frac{4P_1/c}{A_{10} + A_{20}} \tag{3.7}$$

Taking into account eqn. (3.3), the denominator of eqn. (3.6) may be written:

$$\left(A_{10} + A_{20}\frac{S_{12}}{A_{22}}\right)$$

We see, comparing this with the denominator of eqn. (3.7), that the equivalent absorption area A_{20} of room 2 (not counting the coupling surface) does not enter into the energy balance with its full amount, but is diminished by the factor S_{12}/A_{22}, which we call the 'coupling factor' from room 2 to room 1:

$$k_2 = S_{12}/A_{22} \tag{3.8}$$

This factor, which characterizes the difference between the 'single-room' and 'coupled-room' analyses, depends not only on such geometric conditions as the ratio of the coupling area to the total area of room 2 but also on the absorption coefficients of all the surfaces in that room.

If $A_{20} \gg S_{12}$ (that is, if k_2 is very small compared with its maximum possible value of unity), the resultant absorption area for room 1 is $(A_{10} + S_{12})$. This means that the coupling area is to be regarded as an open window, which must be added to the rest of the absorption in room 1. Clearly it would be wrong, in this case, to add the much larger absorption area A_{20} to A_{10}, since it would be impossible to absorb more power from room 1 than enters the coupling area. This limiting case actually occurs for nearly all deep boxes in theaters and for the seating areas underneath deep balconies in auditoriums.

On the other hand, if $A_{20} \ll S_{12}$, the coupling factor S_{12}/A_{22} differs so little from unity that A_{20} can be added directly to A_{10}, in effect treating the two rooms as one.

A reliable decision as to how close we are to one or the other of these two limits requires an exact calculation of the coupling factor. But since the statistical theory of coupled rooms can give only an approximate answer anyway, we adopt the following rule-of-thumb: if the boundary area covered with absorptive materials in room 2 exceeds the coupling area, treat the coupling area as an open window; otherwise, treat room 2 as part of room 1. This rule-of-thumb also applies to the calculation of the reverberation time of room 1, as we shall see below.

The significance of the coupling factor becomes immediately evident in calculating the ratio of energy densities, based on eqn. (3.5):

$$\frac{E_2}{E_1} = \frac{S_{12}}{A_{22}} = \frac{S_{12}}{S_{12} + A_{20}} = k_2 \tag{3.9}$$

If $k_2 \approx 1$ (that is, if $S_{12} \gg A_{20}$), there will not be a significant decrease in loudness as we pass from room 1 to room 2. (The fact that balcony seats are sometimes preferred for their greater loudness may actually result from geometric room acoustics conditions and short delay times, rather than a simple energy balance; these matters lie beyond the reach of statistical room acoustics; see Chapter I.5.)

If, on the other hand, k_2 is small (that is, if $S_{12} \ll A_{20}$), the drop-off of energy density upon entering room 2 is quite evident, an effect that is frequently noticed upon stepping back under deep balconies in auditoriums. (In Section I.5.6 we discussed how this effect can be minimized by geometrical means.)

The loss of loudness is usually not serious in such cases, because our ears can adapt to a lower loudness level. Indeed, the under-balcony seats may even have the acoustical advantage of great clarity of sound (again for geometrical acoustics reasons).

But the loss of loudness of the desired signal may become quite noticeable in comparison with the loudness of an intrusive noise that is produced within the coupled room, 2. Whereas the energy density of the signal in room 2 is decreased by a factor of S_{12}/A_{22}, compared with that in room 1, the energy density of the intrusive noise in room 2 is greater by a factor of A_{11}/A_{22} than the energy density that would be produced by the same noise source in room 1. This means that the ratio of signal energy density to noise energy density in room 2 is smaller by a factor of S_{12}/A_{11} than it would be in room 1 with the same noise source operating there.

This coupling factor concerns the coupling of sounds from room 1 to room 2, so we characterize it by k_1:

$$k_1 = S_{12}/A_{11} \tag{3.10}$$

Since A_{11} is usually very large compared to S_{12}, this coupling factor is usually small.