14 Binaural transfer path synthesis

In this chapter, the acoustic model of airborne and impact sound transmission and the subsequent auralization technique is generalized to other applications in acoustics and noise control engineering. It was shown that the resulting sound pressure signal at the listener's ears can be constructed by using binaural filters. Sound transmitting elements are accounted for by their transfer function to achieve the correct level and colouration. Phase aspects can often be neglected in the diffuse field conditions in the listener's environment. Components of early, primary sound, however, must be modelled with their phase or group delay which enhances the presence and immersion and the correct localization. From these components, sources and transfer paths can be constructed and combined into an efficient auralization model.

Binaural transfer path synthesis (BTPS) is closely related to binaural transfer path analysis.[71] The analysis part is an indispensable tool of acoustic engineering. The applications are manifold in identification and characterization of sources and weak elements of sound transmission and of relevant components of sound radiation. When the acoustic system of generation and transmission is identified and separated into the main sound transmitting paths, the synthesis process can be started. This is possible not only in a simple reproduction of the situation analyzed, but with a variation of the complete system and with exchange of system components. In the example of sound insulation in buildings, the paths of direct and flanking transmission were treated exactly in this way. Adding linings or elastic interlayers in one of the paths is a typical variation of the system which can well be studied with regard to effective sound insulation performance, and it can be auralized for comparison of systems and their variations.

The concept of binaural synthesis, an important component of the concept of BTPS, was introduced in Sect. 9.3. Any monaural sound can be linked to a specific direction of incidence. In addition, sound that carries the characteristics of transmission paths can be modified in loudness and colouration. With these elements, the binaural transfer path synthesis is defined.

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[71] so-called BTPA

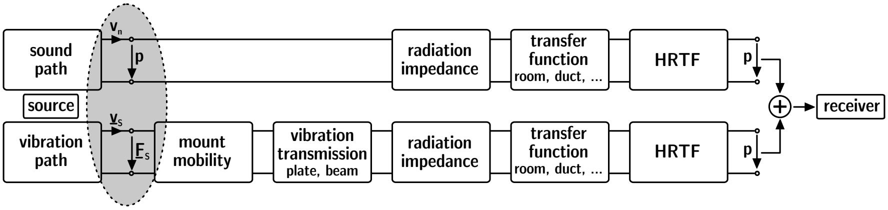

Fig. 14.1. Block diagram of BTPS

Tools for transfer path analysis and synthesis are standard methods in the automotive industry. Early in the design and development of an automobile, the engine and the car body and particularly combinations of both are studied with regard to the structural and acoustical performance. We therefore take the discipline of vehicle acoustics as a leading example in this chapter.

The method of BTPA and BTPS (Genuit and Xiang 1997) is used to optimize products (automobiles and others). The crucial point is that human perception of sound and vibration is part of the process. Thus, feedback from BTPS can help the engineer working on the combustion motor to study the acoustic and vibration performance in relation to the car body and the final recipient (the driver). The goal of BTPS is to determine the sound pressure at the ear canals of a test person (typically called driver's ear), as a sum of all sources and transfer paths. To obtain this result, the resulting signals are separated into their components of primary source signals and transfer functions. The crucial part of BTPS is the definition of appropriate interfaces.

The boxes shown in Fig. 14.1 are two-ports. The upper path represents airborne sound generation and transmission. The source may be modelled as a volume flow source which acts on the radiation impedance. By coupling source and radiation impedance, the effective velocity is calculated. Alternatively, the source can be described by using the sound power or the near-field sound pressure. The source quantity chosen is then coupled to a transfer function and to the listener's ears to obtain a binaural representation. Binaural transfer functions can be measured, predicted or calculated. Interface problems are accounted for by coupling the two-ports, as described in Sect. 10.2.1. Sound radiation and propagation in a room can as well be simulated by using geometric models and binaural filters such as introduced in Sect. 11.6. In general, the lower path contains three degrees of freedom (x, y, z) or up to six, when rotational states are included.

The two-ports include circuits of concentrated components such as springs and masses. For higher frequencies, this approach might be no more adequate. The system might require field quantities distributed in the geometry (for instance, the velocity pattern on a plate or membrane), but still then the velocity distribution may serve as an input quantity if it is derived on a modal functional basis.

The boxes on the right side represent signal processing from the model of physical wave propagation into the listener's dimensions. The sound pressure characteristics of the waves arriving at the ears, addressed to simplified wave fields (plane, spherical etc.) with well-specified angles of incidence, levels and delays are transformed into a head-related binaural signal; see Sect. 9.3.

The efficiency of BTPS was proven in practice, particularly in vehicle acoustics (Sottek and Müller-Held 2007). In automotive engineering, BTPA and BTPS are standard methods for analyzing and optimizing acoustic signals. In noise control engineering for trains and aircrafts, it is used increasingly. The methodology can be applied as well to any other machines, household appliances and devices of daily life (such as, for instance, personal computers, dishwashers or vacuum cleaners). But for better understanding of the concepts, the following discussion is focused on the example chosen, which is automotive engineering.

14.1 Source identification and characterization

The specific behaviour of sources in general is related to the degrees of freedom of vibration and to the radiation of airborne sound. In automobiles, the main source contributing to the resulting car cabin sound is the combustion engine, including gearbox, intake and exhaust system[72]. Simulation and auralization of combustion noise is a challenge, particularly for modern engines with specific electronic injection control and optimized efficiency. The vibration and sound radiation is extremely complex with regard to spatial attributes, near-field effects of noise cancellation and amplification and the complex vibration injected into the car body through the engine mounts. The final result of interest is in any case the sound pressure in the driver's ear canals, as represented in the binaural signal. In Fig. 14.2, it can be observed that the paths are separated into structure-borne and airborne paths. Structure-borne paths (solid lines) contain interfaces of mounts and parts of the car frame body and the radiation of beams and plates into the driver's cabin. Airborne paths (broken line) represent direct airborne radiation of the primary source of the powertrain and sound transmission to the driver's ear.

[72] When driving at high speed, of course, wind noise is another important sound source.

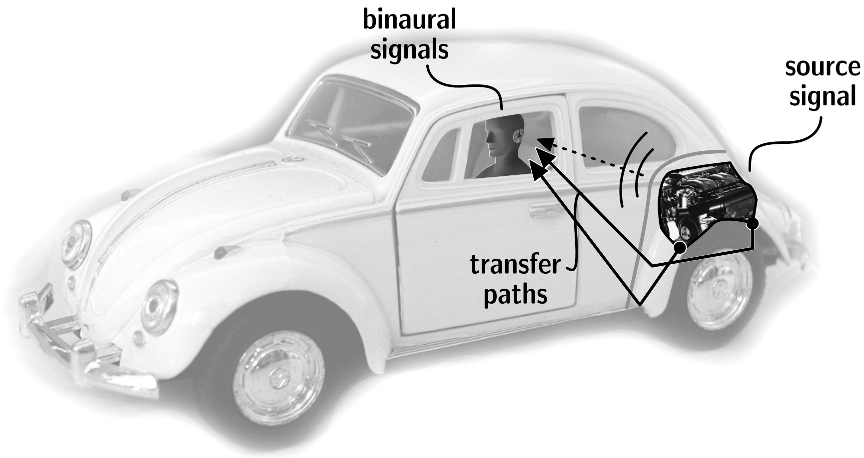

Fig. 14.2. Binaural transfer path synthesis for simulating in-cabin sound[73]

Transfer path determination and interfacing to the source is the key to creating BTPS. Here we have to face two problems:

- In the component of airborne sound, the complexity of vibrational modes may be much larger than the number of transfer functions practically available. This is the main problem discussed in Sect. 14.1.1.
- In the component of vibrational force, feedback between the source and the transfer function is significant. This is the main problem discussed in Sect. 14.1.2.

14.1.1 Airborne sound sources

We start again by discussing vehicle sound and the combustion engine. For airborne sound transmission, the motor must be characterized as a primary source. The motor block is heavy and stiff. Vibration of the engine body induced by the engine operation is not at all affected by the acoustic load of the fluid medium (air). Thus, the source acts as an ideal velocity source. We don't have to take feedback at the interface between source and transfer function into account. Instead, severe difficulties must be faced when the specific pattern of the source vibration must be described in detail. The engine surface neither moves in a purely breathing mode nor like any other multipole. The modal pattern is a complex phenomenon which can only be studied by using structural models such as FEM or a detailed experimental

[73] This example illustrates BTPS for a vehicle with a rear engine. It is also applicable, of course, to cars with front engines.

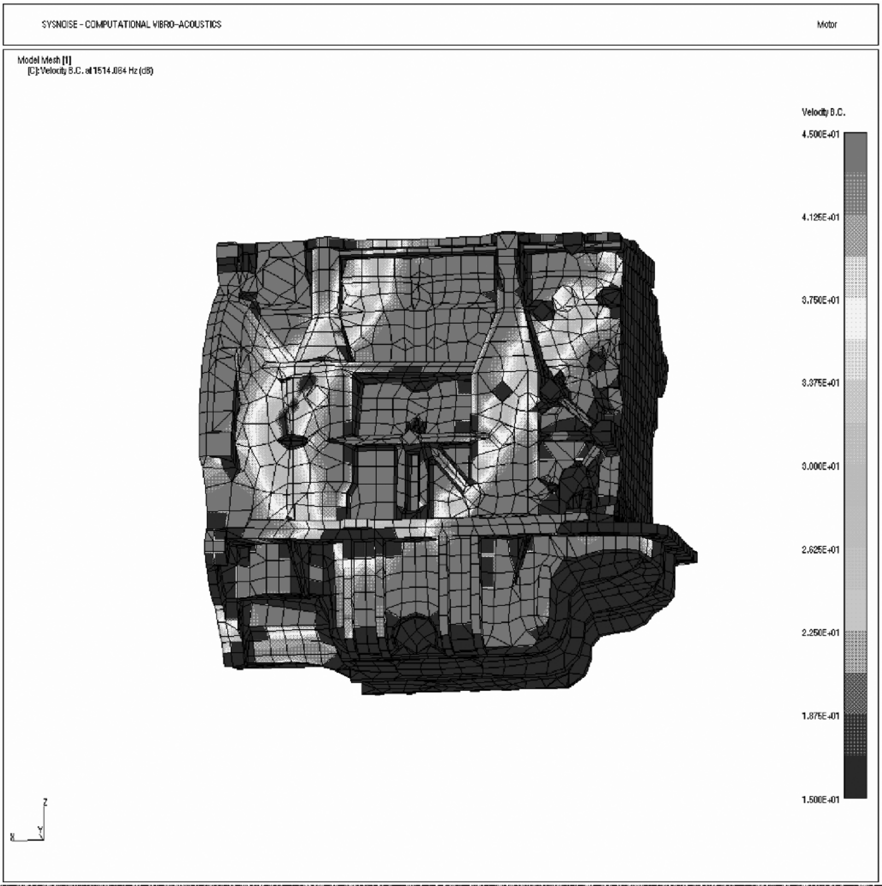

Fig. 14.3. Vibrational distribution on a combustion engine. Measurement result by using a scanning laser vibrometer

modal analysis.[74] These methods can be used directly to determine the surface velocity distribution.

The actual vibrational pattern can also be approximated by using parameter sets of multipoles (Sect. 2.4), spherical harmonics (Sect. 2.5) or the technique of pressure mapping for acoustic holography (Williams 1999). The advantage of these techniques is the reduction of parameter complexity. They have in common that sound pressure measurements at well-chosen field points are used as input data for mathematical reconstruction of the surface velocity. In some cases. this technique is called "acoustic camera." It is clear that special conditions such as an anechoic environment are required. For further processing in BTPS, the parameter

[74] by using laser Doppler vibrometry, for example.

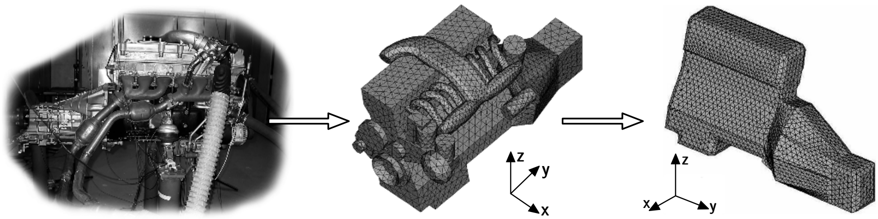

Fig. 14.4. Volume-conservative steps to create an engine model for BTPS (Römer 2004)

sets of multipoles, spherical harmonics or pressure maps are used as intermediate source data. But BTPS for airborne sound sources in vehicles now suffers from the problem that distributed acoustic fields must be matched to a model of concentrated two-port elements for the transfer paths. Unless the approach is not extended to a finite element approach, therefore, the method applied is not consistent physically, but is an approximation for acoustic engineering, whose validity must be checked in each application.

When engine data are obtained in situ, i. e., in the engine compartment at the engine mounted inthe car, the vibration on the surface and the source signal can only be estimated. This simplified approach is possible when the acoustic field in the engine compartment is dominated by cavity modes. The forced response excited by the engine is then close to the resonant cavity response which allows us to model the source by estimating the total volume flow, while the actual vibrational pattern is ignored. However, the validity of this approach must be checked carefully, too.

In any case, the engine must be represented by its actual volume, inserted into the model of the engine compartment and coupled to the transfer functions. Until a closed solution of coupling is feasible, proper transfer functions and interfaces must be chosen in a way that all relevant acoustic effects are captured. An overall system modelling solution, of course, is the only approach with high precision. Here, we insert the engine mesh into a finite element model of the whole car including numerical wave prediction in air and structural modes which creates quite a challenge for numerical calculation.

Other sources of airborne sound in the vehicle are a) smaller and b) less complex regarding the modal response. The problems there are given by the necessity of describing the source by an air flow, such as in the intake and exhaust system, or tonal components such as in the electric generator or in the turbo compressor. In a (slowly) pulsating DC flow the (acoustic) AC component of sound is difficult to measure. In the exhaust pipe, the “effective” source may also be given by an axial line source due to pulsating jet development. Tonal components require more precise phase responses and transfer functions. Numerous other practical aspects and difficulties, which cannot be discussed in detail here, must be considered in specific problems.

One important task to be explained in more detail is that of measuring sources and transfer functions in situ. In the in situ measurement, two aspects are important. The interface between the source signal and the transfer function must be defined. If source signals from free field conditions in test facilities are used as input signals, the transfer function must match this condition. On the one hand, the access to an equivalent measurement point in the engine compartment is difficult, and the choice of the set of measurement points is thus restricted to the accessible points. On the other hand, the relative and absolute calibration of the transfer function is difficult due to cross talk between the measurement points and due to a somewhat arbitrary distance and near-field effect.

Nevertheless, it is possible to apply BTPA and BTPS based on in situ measurements, if the calibration is adjusted between the test facility and in situ conditions. These calibration spectra can be obtained by experiment, too.

14.1.2 Structure-borne sound sources

Structural paths are not as multidimensional as airborne sound fields.[75] The number of paths and degrees of freedom are relatively low, and the signal flow over these paths can be modelled consistently inside BTPS by using the two-port approach. The engine is typically fixed on three points by using rubber or other viscoelastic mounts. With three degrees of freedom for translational and another three for rotational movement, the total force and torque can be modelled. The impedance of the car body, however, affects the vibration injected. The signal flow, thus, is to be modelled by taking feedback into account (see Sect. 10.2.1).

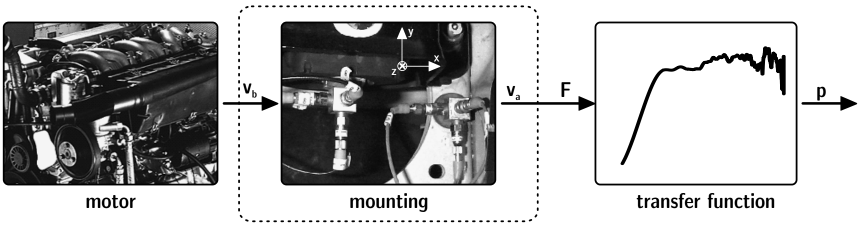

Fig. 14.5. Primary vibrational source connected to mount and transfer function (Sottek et al. 2005)

[75] which is true at least for structures with point or line contacts.

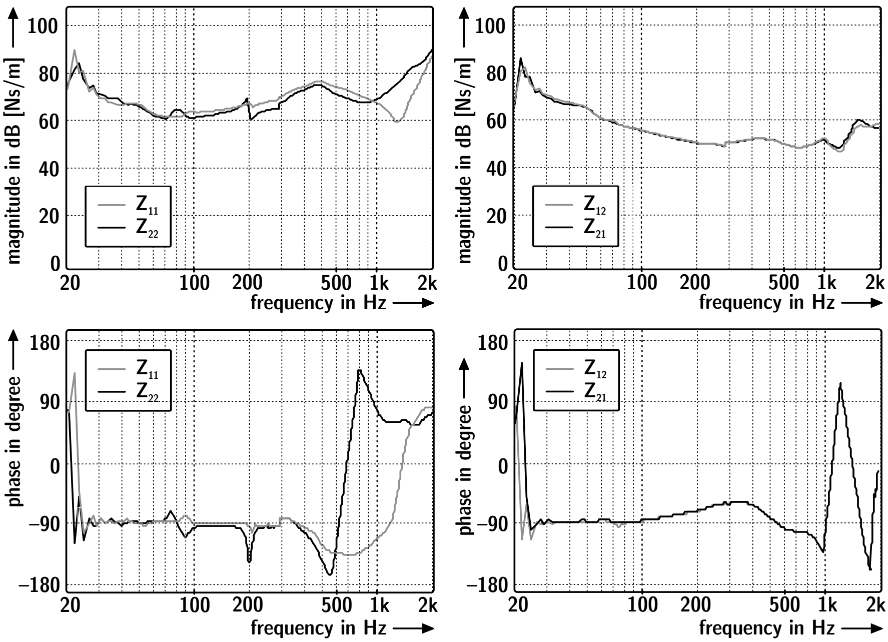

Fig. 14.6. Transfer impedance of engine mounts (Dohm 2004)

Well-defined load impedances are a prerequisite for proper transfer path characterization. The primary engine vibration is usually measured in a free condition, assuming an ideal velocity source. The mount mobilities and other two-port parameters are determined in a special test stand for free and blocked-force conditions. Examples are shown in Fig. 14.6.

14.2 Transfer path characterization

In BTPS, sound and vibration propagation from the source to the receiver are modelled by transfer functions or transfer impedances. They are defined in each specific case on the basis of sound pressure spectra at the binaural receiver to the source quantity defined. For airborne sound components, the transfer functions are Green's functions (see Sect. 10.1); for vibration components, two-port matrices are used. Binaural filters are introduced in the end to account for the direction of sound incidence.

In a straightforward approach, transfer function filters can also be measured between the source and the receiver's ears directly. The source arrangement (see Sects. 14.1.1 and 14.1.2) is thus connected to the receiver's ear by filters, whose number coincides with the number of source signals recorded.

For each source point, this measurement must be performed separately and independently to avoid cross talk between paths. In the example of a transfer function between the vibration source velocity and the ear sound pressure, the direct measurement required a calibrated excitation of vibration, such as excited by a shaker or an impulse hammer, for instance. The sound pressure at the receiver is measured by using a dummy head for all paths, one by one.

In a reciprocal arrangement, however, all paths can be measured in parallel. Due to vibroacoustic reciprocity (see also Sects. 10.1 and 10.2), the ratio

$$H = \left. \frac{p_{\text{receiver}}}{F_{\text{source}}} \right|_{v=0} \tag{14.1}$$

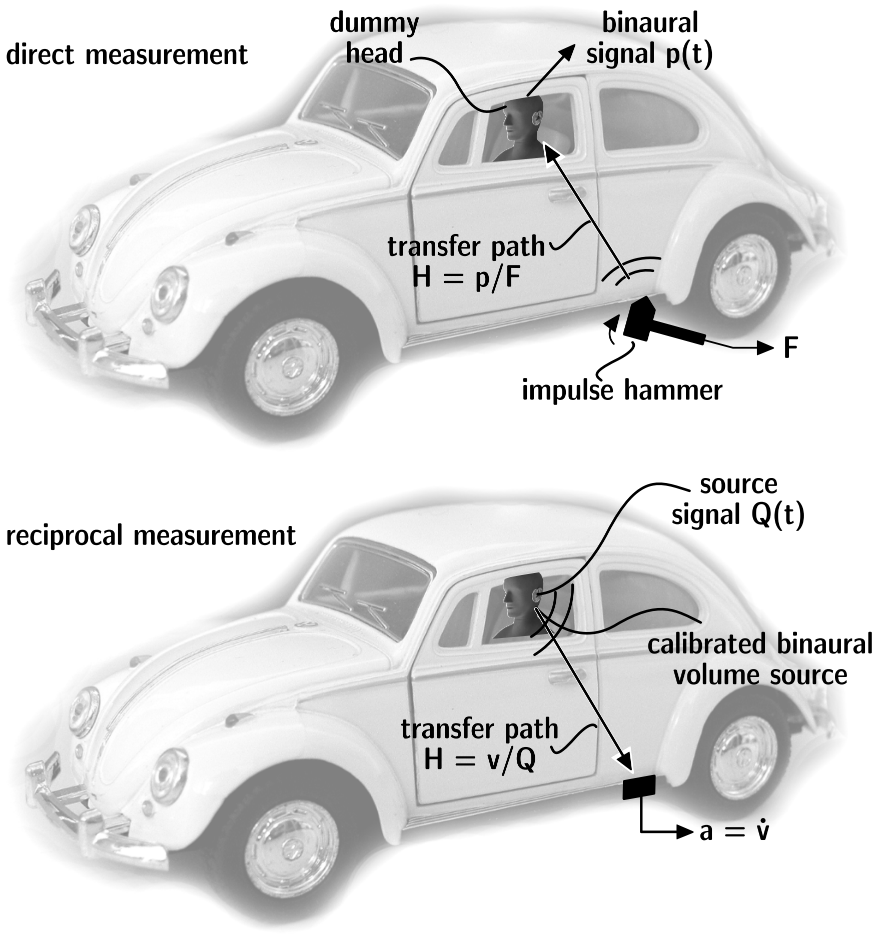

Fig. 14.7. Measurement of vibroacousic transfer functions (see also (Sottek 2004; Sellerbeck 2003))

is equivalent to

$$H' = \left. \frac{v_{\text{eq,source}}}{Q_{\text{eq,receiver}}} \right|_{F=0} = H \, . \qquad (14.2)$$

With a calibrated volume source (reciprocal dummy head) at the receiver and accelerometer placed at the structure's source point(s), the transfer function is obtained (see Fig. 14.7).

14.3 Auralization in BTPS

When the primary source is recorded in operation, such as an engine running at increasing speed (rpm), this signal serves as an input for binaural

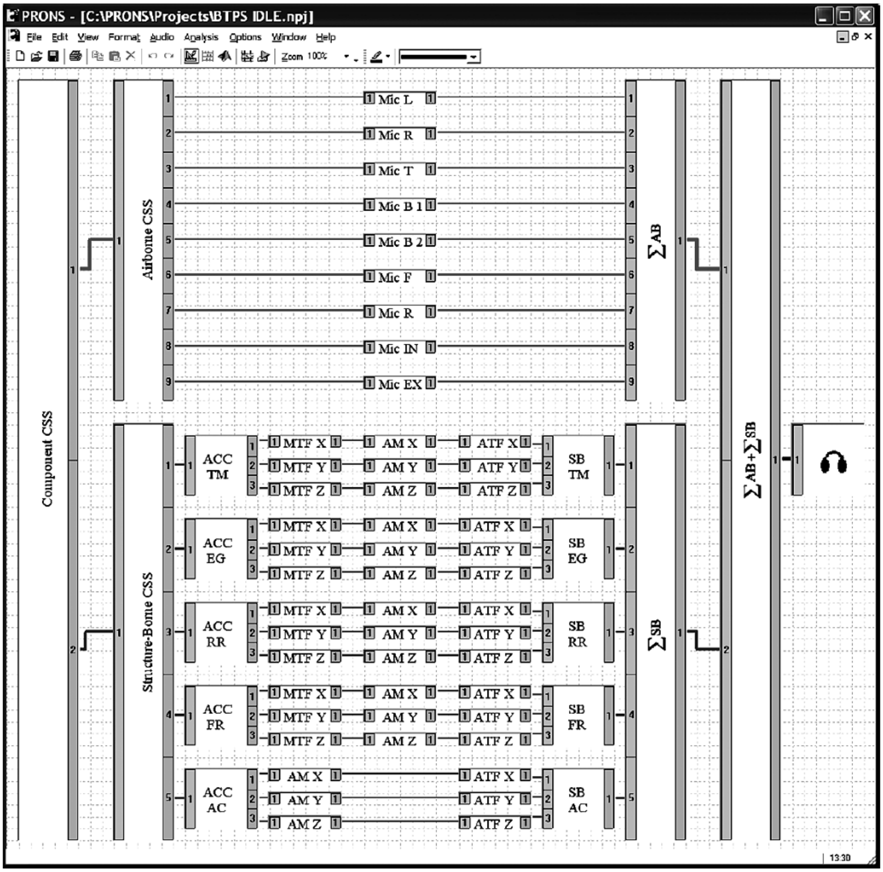

Fig. 14.8. Example of a BTPS software user interface (after (Sottek et al. 2004))

transfer path auralization. The filters and coupling impedances are used in network components in the two-port mode described above. The signals are processed in convolution units.

The big advantage for the sound engineer is that transfer paths can be added, switched off or modified, depending on the specific choice of system parameters. Other sources may be added too, such as wind noise or tyre noise. Integrated into a driving simulator, the binaural transfer path auralization allows detailed psychometric tests on sound character and sound design targets.

As described above, the synthesis is based on input measurements in the engine compartment of cars or on an engine test rig. It is typical, however, that during the development of new engines, car prototypes are not yet available. Therefore, recent extensions of BTPS involve more and more simulated sound transmission data for airborne and structure-borne paths or a combination of measured and simulated data. The challenge for future work is the combination of finite element models, SEA models and two-port models in different frequency ranges. Also of interest is the variability of input data on material properties and the variability of junctions, related to the variation of those parameters in the production process.

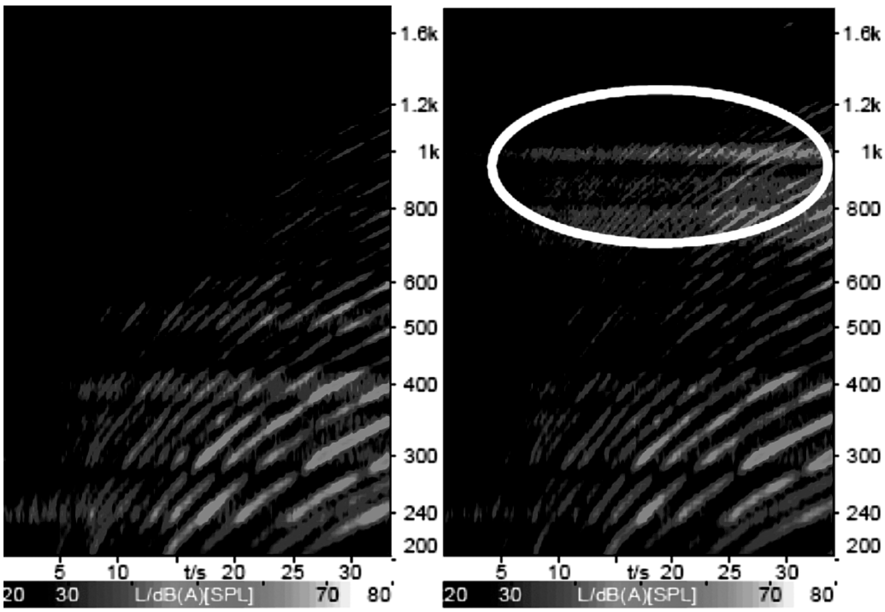

Fig. 14.9. Example of spectrograms showing the effect of changing engine mounts by using BTPS (after (Behler et al. 2006))

The increasingly sloped curves in Fig. 14.9 illustrate an increasing rpm. A combustion engine is mounted in the car body by using two different engine mounts (different stiffness). The time and the frequency, respectively, are shown on the abscissa and the ordinate. The sound level in dB(A) is presented in a grey scale. On the right-hand side, the resonance effect illustrates a suboptimal impedance match between engine mount and car structure. An rpm-independent spectral maximum appears between 800 Hz and 1 kHz which creates an unwanted vehicle sound character. Hence, the target sound is better achieved by using the mount with the result shown on the left side.