1

Introduction

1.1 Automotive Body Structure and Noise and Vibration Problems

1.1.1 Automotive Body Structure

An automotive structure, including the body, power train, suspension, and so on, is very complex. The main systems of the vehicle are “hung” on the body – for example, the power plant is connected with the body by mountings, the suspension is connected with the body by bushings or directly connected with the body, and the exhaust system is connected with the body by hangers – so the body is a core of the vehicle and determines the vehicle’s performance. However, the body is also a place for carrying passengers, so its structural characteristics directly influence the perception of the vehicle’s users.

1.1.1.1 Unitized Body and Body-on-Frame

There are two major forms of automotive structure: the unitized body and the body-on-frame. When the body and the chassis frame are integrated as a whole structure, as shown in Figure 1.1, this is known as a unitized body, also called an integrated body or integral body. The unitized body itself takes the load of vehicle, rather than the load being taken by an independent frame. The advantages of a unitized body include its simple structure, small size, light weight, and low cost, but its disadvantage is that the body’s loading capacity is limited. Most passenger vehicles have a unitized body.

Body-on-frame, also called a separate frame structure, non-integrated body, monocoque, or body chassis frame construction, is a body structure in which the chassis frame is separated from the body. The chassis frame, which has high structural strength, is arranged below the body. This structure has the advantages of high stiffness, high strength, strong loading capacity, and strong capacity to resist bending deformation and torsion deformation, but the disadvantages are that the structure is complex, heavy, and expensive. Trucks, buses, off-road vehicles, large sport-utility vehicles (SUVs), and a small number of passenger sedans use a body-on-frame structure.

The noise and vibration problems and control methods described in this book are based on the unitized body structure, so throughout, “body” refers to the unitized body. In automotive engineering, vehicle noise and vibration is usually denoted by “NVH”, for noise, vibration, and harshness. Harshness represents the subjective sensation on the human body of vehicle noise and vibration.

Noise and Vibration Control in Automotive Bodies, First Edition. Jian Pang.

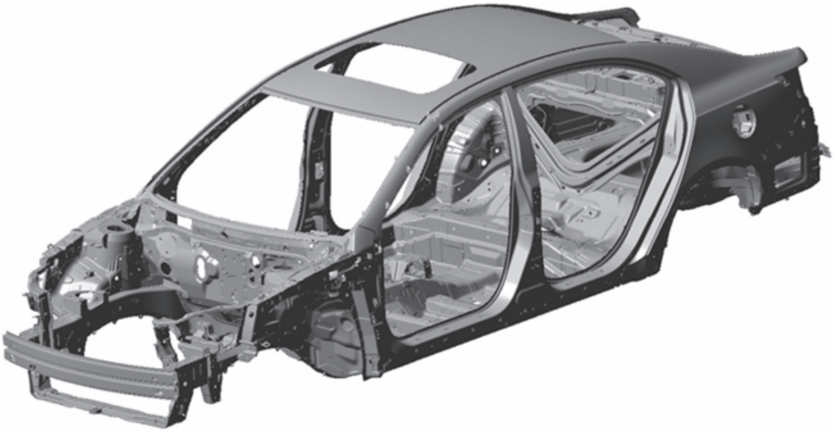


Figure 1.1 Structure of a united body.

Figure 1.2 Structure of a trimmed body.

1.1.1.2 Body-in-White, Trimmed Body, and Whole Vehicle Body

The stages of construction of a vehicle body are divided into the body-in-white (BIW), the trimmed body, and the whole vehicle body. The BIW refers to a body consisting of frames and panels, including front and rear side frames, rocker frames, cross members, dash panel, floors, roof, and front and rear windshields. Sometimes the BIW is further divided into a BIW without windshields and a BIW with windshields. The BIW without windshields refers to the welded body structure, as shown in Figure 1.1.

The doors, trimmed parts, and seats are installed on the BIW to form the trimmed body, as shown in Figure 1.2. The trimmed body includes the BIW, doors, engine hood, trunk lid, seats, steering system, sound absorptive materials, and insulators.

After the trimmed body and other systems, such as the power plant, exhaust, and suspension, are integrated into the vehicle, the body is called the whole vehicle body. The structures of the whole vehicle body and the trimmed body are the same, but their boundary conditions are different. The body in a whole vehicle is connected with other systems, so it is subjected to constraints from these systems.

1.1.1.3 Classification of Body Structure

Body design involves many performance attributes, such as NVH, crash safety, fatigue and reliability, fuel economy, and handling. The body can be classified by each attribute according its characteristics. In this book, the body is classified from the perspective of NVH. The body is divided into four categories of structure according to its NVH functions, namely the frame structure, panel structure, trimmed structure, and accessory structure, as shown in Figure 1.3. The frame structure refers to a body frame comprising side frames, cross members, and pillars that are connected by the joints. The panel structure refers to the metal plates that cover the body frame, such as the dash panel, roof, floor, side panels, and door panels. The trimmed structure refers to the parts that reduce noise and vibration, such as the dash insulator and damping structure. The accessory structure refers to the accessory parts installed on the body, such as the steering shaft, mirrors, and seats. The make-up and functions of these four structures are briefly described below.

The frame structure, as shown in Figure 1.4, is the foundation of the body. The frame is composed of front and rear side frames, cross members, pillars, and so on. Several side frames, cross members, and pillars intersect, forming a joint. The cross section,

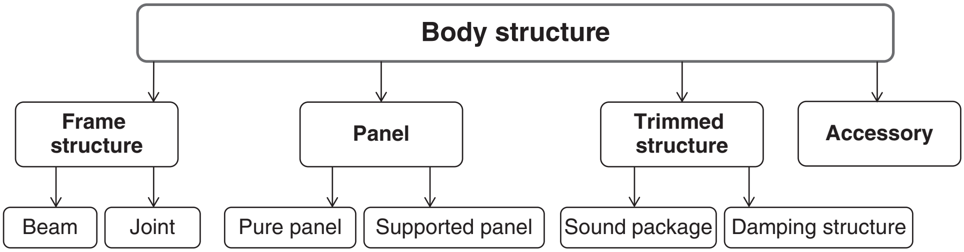


Figure 1.3 Classification of body structure.

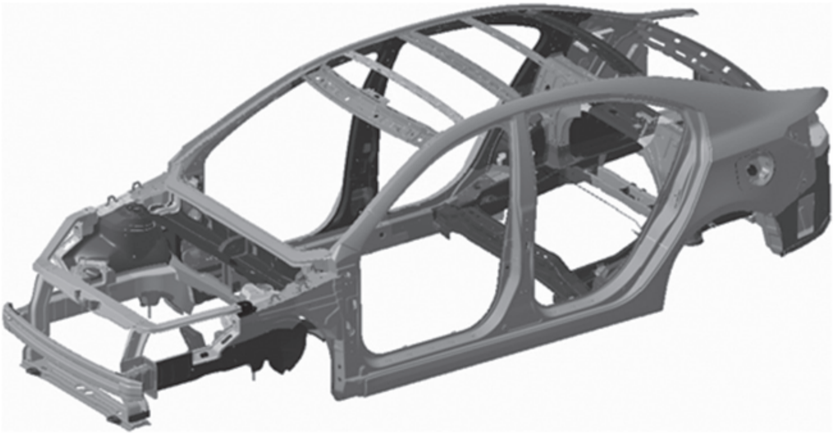


Figure 1.4 Body frame structure.

size, and span of a beam determine its stiffness. The joint has significant influence on the body frame stiffness. The frames can only be tightly intersected if the joints have sufficient stiffness. If the frames are stiff enough, but the joint is weak, the stiffness of the body frame is still weak. Therefore, the stiffness of the body frame is determined by both the frame stiffness and the joint stiffness, while the body frame stiffness determines the modal shapes and frequencies of the vehicle body.

The panels are mounted on the frames to form an enclosed body space. The panels are divided into pure panels (or local pure panels) and supported panels. A pure panel is one without support, such as the fender shown in Figure 1.5. Most body panels are supported by metal beams or reinforcement adhesives, or have beaded surfaces, so this kind of panel is called supported panel. Examples of supported panels include the outer door panel (Figure 1.6), where the internal side is supported by the side-impact beam or

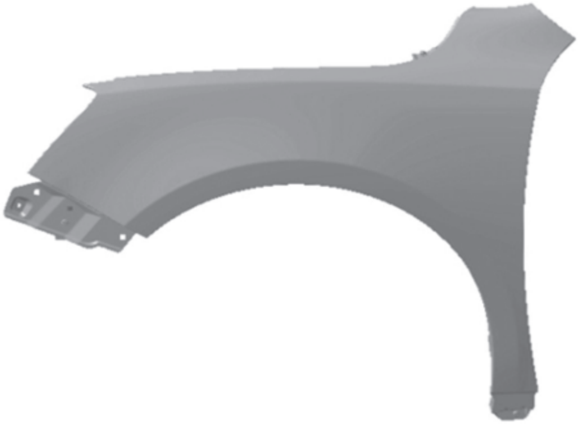


Figure 1.5 Fender.

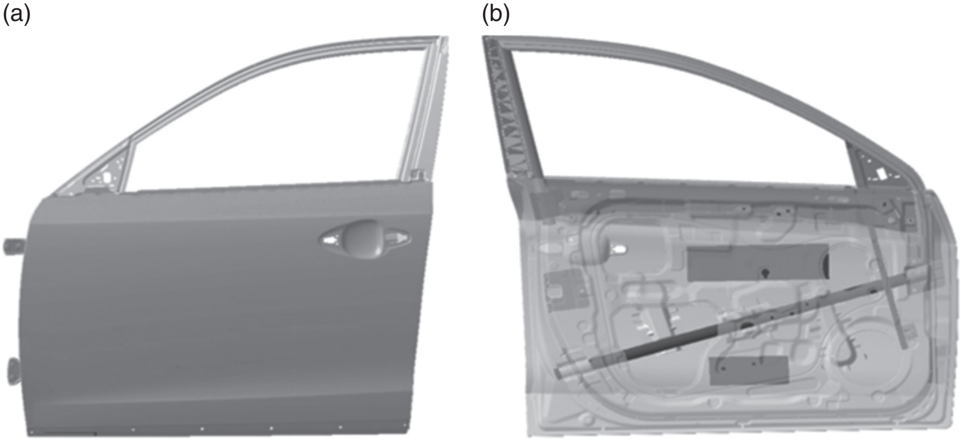


Figure 1.6 A door panel. (a) Outside. (b) Internal side.

reinforcement adhesives, and the beaded floor (Figure 1.7), which is supported by the cross members. Sometimes, it is difficult to distinguish between a pure panel and a supported panel, as in the case of the roof shown in Figure 1.8. The roof is a big panel supported by several cross rails, but some area of the roof between two rails is so large that it can be regarded as a pure panel.

The trimmed structure bonded to the panels and frames includes decoration parts that also function to absorb and insulate sound and non-metallic parts that suppress the transmission of noise and vibration. From the NVH perspective, the trimmed structure can be divided into four categories: sound insulation structure, sound absorption structure, damping structure, and barrier structure. The sound insulation structure includes the dash insulator and carpets. The sound absorption structure includes the headliner and the sound absorption layer of the dash insulator. In most cases, the sound insulation structure and the sound absorption structure are integrated to form a sound-absorption-insulation structure, such as the dash inner insulator, as shown in Figure 1.9. The damping structure refers to the damping layer on the panels, including damping material on the floor, as shown in Figure 1.10, and the constrained damping layer installed on panels such as the sandwiched dash panel system shown in Figure 1.11. The barrier structure is a special foaming structure placed inside the frame cavities in order to

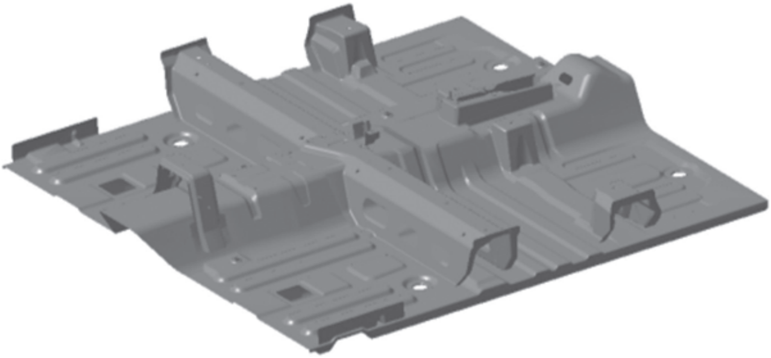


Figure 1.7 A floor.

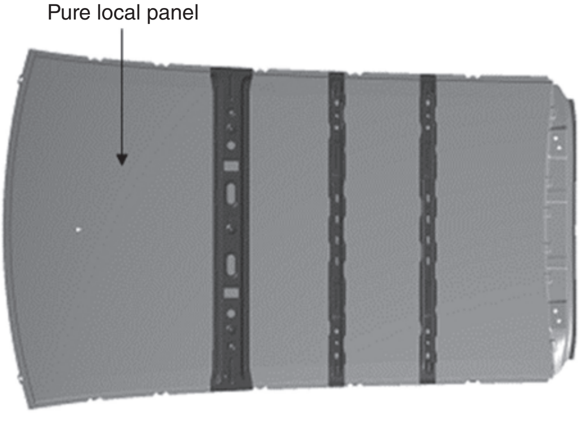


Figure 1.8 A roof.

Figure 1.9 A dash inner insulator.

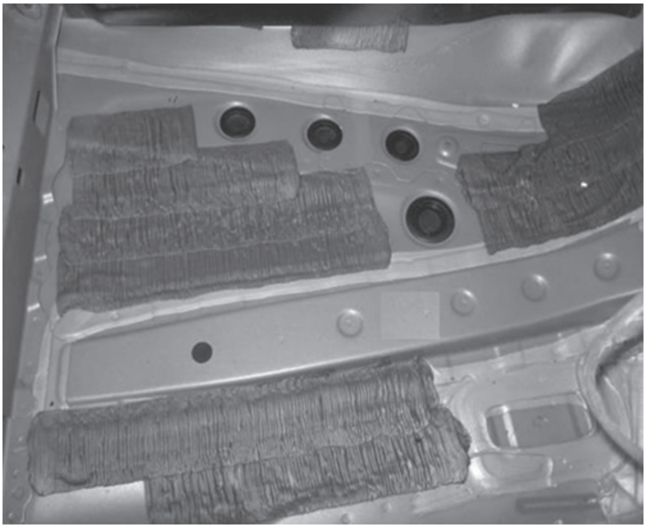


Figure 1.10 Damping material on floor.

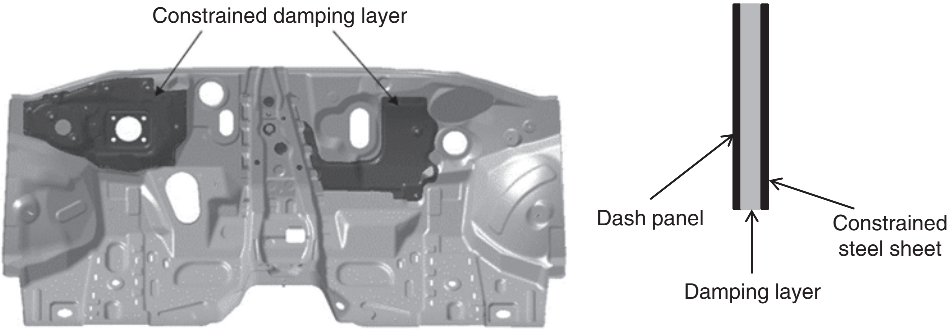
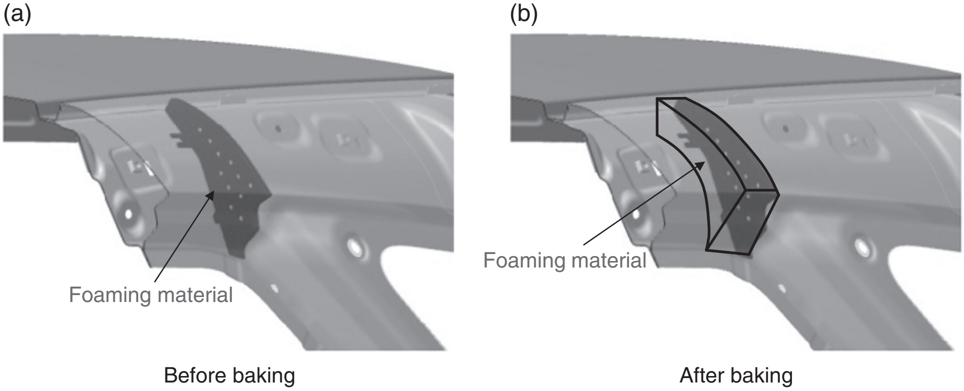


Figure 1.11 A sandwiched dash panel system.



Before baking After baking

Figure 1.12 Foaming material inside a frame cavity.

prevent sound transmission. The volume of the foaming material is small, but after being baked in high temperature environment, it expands and its volume increases dozens of times, filling a section of the frame cavity, as shown in Figure 1.12.

The accessory structure refers to the other structures installed on the body, such as the steering shaft system, instrument panel, seats, shift system, and mirrors. Occupants may directly perceive vibrations induced by these structures.

1.1.2 Noise and Vibration Problems Caused by Body Frame Structure

The frame structure is the basis of the body, in the same way that a frame is the basis of a building. If the housing framework is not well constructed, its capacity to carry load and resist earthquakes will be deteriorated, and the house could even collapse. A poorly designed and constructed body frame will generate many problems, such as resonance, body deformation, squeak and rattle (S&R), and even safety issues.

The body frame is the supporting structure for other parts, such as the doors, panels, engine hood, trunk lid, and accessory brackets. If the stiffness of the frame structure is insufficient, the door and other components will not be well supported. Under low excitations, friction between these components and the frame could be generated. Under impulse excitations, the components could impact each other. Friction and impact between components are two major causes of S&R.

Over a long period of vibration and shock excitation, the body frame may deform, resulting in poor fitting between the doors and the body frame, and deterioration of body sealing performance. During high-speed driving, the dynamic sealing will be particularly poor, resulting in a huge wind noise.

Excitations from the engine and road directly act on the body frame. These excitations are dominated by low-frequency components. If the frame structure does not have sufficient stiffness, i.e. its modal frequency is low, the body can be easily excited, resulting in the body resonance.

The body frame affects not only the NVH performance, but also crash safety, handling performance, reliability, and so on. For example, the effect of a head-on collision is directly related to the structure of the front frames and cross members.

The frame structure usually induces the low-frequency vibration and noise problems that affect overall vehicle NVH performance. Therefore, the stiffness and modal frequency of the frame structure are very important. Body stiffness can be controlled from two aspects, i.e. the frame and the joint; for both, the stiffness should be as high as possible.

1.1.3 Noise and Vibration Problems Caused by Body Panel Structure

A body panel is similar to a piece of paper or a drum. When the paper is waved in the air, the paper hums because it vibrates and radiates sound. When the drum is hit, the drumstick applies a force to the drum surface, which vibrates and generates sound.

The body is connected to many systems that generate excitations, such as the engine, exhaust, and suspension. In addition, when a vehicle is driven at high speed, the wind excites the body. When subjected the external excitations, the body panels vibrate and generate sound, just like a piece of paper or a drum.

The vibration and noise problems generated by the body panels are divided into two categories: one is the direct radiation of sound, and the other is the interior booming caused by the coupling between a panel and the body cavity.

Under an external excitation, the panel vibrates and radiates sound because of its thin and large surface. To reduce this, the body panel should be designed to be as stiff as possible, and large flat surfaces should be avoided. Usually, there are three ways to increase the frequency of the panel. The first one is to bead the panel to form an intertwined structure. The second one is the use of convex design, i.e. the panel is designed as several planes or arcs. The third one is to add support to the panel. In some cases, if the frequency of the panel cannot be increased by the above methods, damping treatment may be implemented. There are two types of damping treatment: free damping and constrained damping. A layer of damping material is pasted onto the panel to form free damping, such as the damping on the floor, whereas a layer of sandwiched damping structure is added onto the panel to form constraint damping.

The reason for interior booming is resonance between a body panel mode and the acoustic cavity mode. The air inside the body is an enclosed space that forms an acoustic cavity with specific modal shapes and frequencies. For example, the first cavity mode is along the vehicle's longitudinal direction and its frequency is low. When the modal frequency of a panel perpendicular to the direction (such as the trunk lid) is the same as the frequency of the first cavity mode, and the panel is excited by an external excitation with the same frequency, the coupling between the structure and the cavity will generate an annoying low-frequency booming that makes occupants uncomfortable.

Most noise and vibration problems generated by body panels are low- and middle-frequency ones, but they also induce a few high-frequency noise problems. These problems are mainly caused by local body structures, so it is very important to control the stiffness and damping of the local structures in order to suppress NVH problems.

1.1.4 Interior Trimmed Structure and Sound Treatment

The trimmed structure itself does not create NVH problems: in fact, it prevents or attenuates sound transmission. The special trimmed structure includes the sound insulation structure, sound absorption structure, and barrier structure. However, the general trimmed structure represents a combination of the special trimmed structure and the damping structure.

The sound absorption structure is composed of absorptive materials, and its function is to eliminate middle- and high-frequency noise. The sound insulation structure is composed of sound insulation material, and its function is to eliminate low- and middle-frequency noise. Usually, the sound insulation structure and sound absorption structure are combined to form a sound-absorption-insulation structure. When outside sound hits the body, some is reflected, and the rest passes through the body and enters the interior. The function of the sound-absorption-insulation structure is to attenuate the penetrated sound. If the structure is not well designed, this function cannot be realized.

The barrier structure prevents outside sound passing through the frame cavities and into the interior through the use of baffling materials. Most body frames, such as A-pillars, B-pillars, C-pillars, side frames, and rockers, are tube-like structures. There are holes on the frames and pillars that are designed for manufacturing processes or for the installation of other components. The outside sound travels inside the hollow frames or pillars, and then enters the interior through the holes. Therefore, the internal channels of the tubes must be blocked with baffling materials in order to prevent the sound transmission. The baffling material is a foaming material: i.e. the original, small-sized material is inserted into a section of a frame or pillar, then after baking in a high temperature environment, it expands and firmly fills the inside of the tube.

The damping structure is a layer of damping material that is placed on the surface of a metal sheet or sandwiched between two sheets. The function of the damping structure is mainly to reduce vibration and noise in the range of 200–500 Hz.

1.1.5 Noise and Vibration Problems Caused by Body Accessory Structures

Body accessory structures can be divided into three categories: bracket, steering system, and seat.

Many components, such as side mirrors, the internal mirror, the battery, the CPU control unit, and the glove box, are mounted on the body by brackets. If the stiffness of these brackets is insufficient, the components will vibrate. For example, insufficient stiffness of the side mirror bracket gives it a low modal frequency. During cruising, the mirror is easily excited by engine or road vibration, so the mirror could shake, affecting the driver's vision. In another example, a battery bracket with low stiffness causes the bracket-battery system to have a low frequency. The system can be easily excited by road input, and the bracket could generate a low-frequency roaring. Therefore, the frequencies of these brackets must be high enough to separate the systems' frequencies from the excitation frequencies of the engine and the road.

The steering system, consisting of the steering shaft system and the cross car beam (CCB) system, is a large accessory. It is also connected to the body through brackets. If the stiffness of the steering shaft system and/or CCB are insufficient, the modal frequency of the steering system will be too low to be coupled to the engine excitation frequency, causing the steering wheel to vibrate. Even if the steering shaft and CCB are stiff enough, the system modal frequency could still be low if their connections to the body are weak, thus it could fall into the external excitation frequency range and cause vibration on the steering wheel. Therefore, the whole system – the steering shaft, CCB, and brackets – must be sufficiently stiff to prevent vibrations. In addition, some components, such as the CD box, are connected with the CCB through brackets, so these brackets should have sufficient stiffness.

The seat is an accessory that the occupants directly touch, and the vibration perceived by occupants involves two aspects. The first perception is the seat's overall longitudinal and/or lateral vibration: i.e. the seat's low-frequency longitudinal and/or lateral modes are excited by the engine or the road. The second perception is that the occupants feel uncomfortable because of an unsuitable design of seat cushion and back cushion that results in poor vibration isolation.

1.2 Transfer of Structural-Borne Noise and Airborne Noise to Interior

The process of noise and vibration transfer from the outside to the interior can be described in three stages: source, transfer path, and receiver, as shown in Figure 1.13. The following materials describe the transfer process from the source.

1.2.1 Description of Vehicle Noise and Vibration Sources

The noise and vibration sources are outside the body. The vehicle is subjected to three sources of noise and vibration: power train excitation, road excitation, and wind excitation. The three sources are briefly described below.

The power train system includes the engine, transmission, intake system, exhaust system, and drive shaft. They are directly connected with the body, so the sources of noise and vibration are directly applied to the body. A distinctive feature of the sources is that the noise and vibration is closely related to the engine speed and firing order. They are the most important sources for interior noise and vibration during idling and at low vehicle speed.

The interaction between the tires and the road generates noise that is directly transferred into the interior. Simultaneously, the vibration generated by the action between the road and the tires is transmitted to the body through the suspension system. This type of noise and vibration is related to vehicle speed, and also to the parameters of the tire and suspension system. The road/tire noise is the major interior noise source when a vehicle moves at middling speed, especially on rough roads.

When the vehicle runs at high speed, wind strongly acts on the body. The noise generated by friction between the wind and the body, called wind noise, is transmitted to the interior through the body. At the same time, the wind excites the body panels, and the excited panels radiate noise to the interior. Wind noise is closely related to vehicle speed. Generally, when the vehicle travels at high speed (e.g. above 120 km h^{-1}), the wind noise will overwhelm the power train noise and the road noise, making it the largest noise source.

Figure 1.13 Source–transfer path–receiver model.

These three noise and vibration sources are transmitted into the interior in two ways: via the airborne sound transmission path and via the structural-borne sound transmission path.

1.2.2 Structural-Borne Noise and Airborne Noise

1.2.2.1 Airborne Noise and Transmission

As the name suggests, airborne noise refers to sound transmitted through the air and then heard by the occupants. Figure 1.14 shows the transfer process of a drumming sound to people outside and inside a house. When the drum is hit, the sound generated by the drum membrane directly transfers to the person standing outside the house. The sound is called airborne sound because it is generated and transmitted in the air, and then heard by the person.

The person in the house can still hear the drumming sound, but the sound level that the person hears is lower than that heard by the person standing outside the house. When the drumming sound transfers to the house, the sound is partially reflected by the walls, doors, windows, etc., with only a portion of the sound entering the house. The drumming sound wave outside the house is called the incident wave, the sound wave reflected by the walls is called the reflected wave, and the sound wave that passes through the wall and enters the house is called the transmitted wave. The sound wave heard by the person inside the house is the transmitted wave.

Many sound sources heard by a vehicle's occupants are airborne noise, i.e. the sounds transmit directly to the occupants through the air. The vehicle body is similar to the wall of a house. When the outside noise hits through the body, some sound waves are reflected back, while others pass through the body and enter the interior (although some sound waves are also absorbed by the body itself). One difference between a vehicle and a house is that a lot of sound absorptive materials and sound insulators are installed on the body, which absorb and insulate some of the sound waves. Figure 1.15 shows the transfer process of the airborne noise to the occupants' ears.

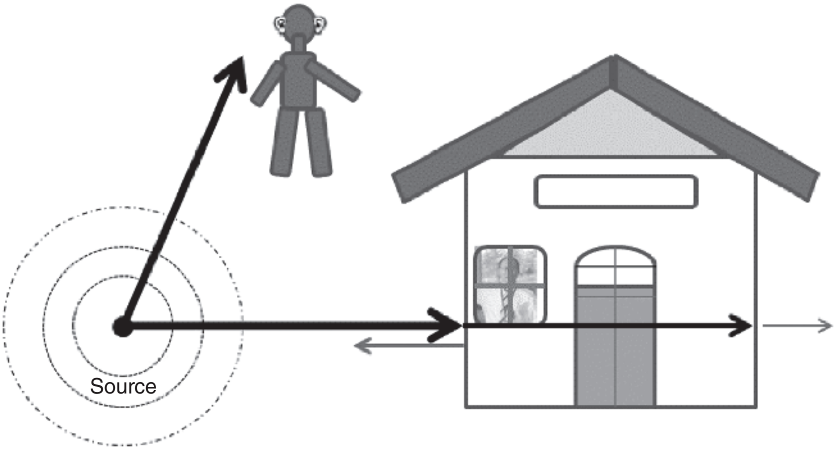


Figure 1.14 Transfer process of drumming to occupants: airborne noise.

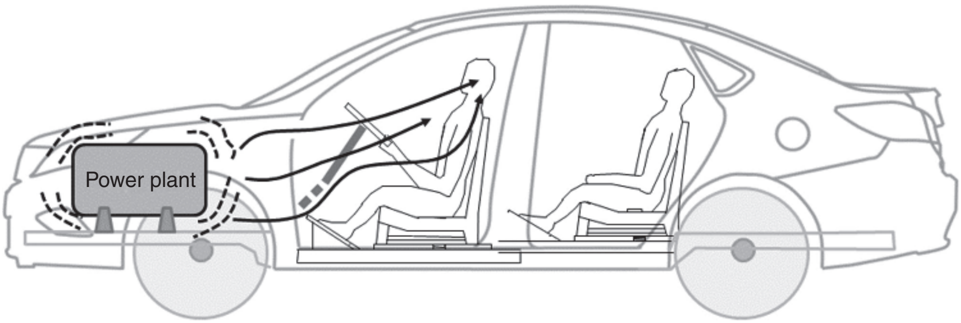


Figure 1.15 Transfer process of airborne noise to occupants' ears.

Figure 1.16 Transmission of structural-borne sound in rails.

The airborne noise sources directly transmitted into the passenger compartment include:

- power plant radiation sound
- intake orifice noise
- exhaust orifice noise
- driveline radiation noise
- noise generated by the cooling fan
- road noise
- wind noise.

1.2.2.2 Structural-Borne Noise and Transmission

Airborne sound is directly transmitted to human ears, whereas structural-borne sound is indirectly transmitted. As the name implies, structural-borne sound refers to sound transmitted in a structure, then radiated to the air, and finally heard by human ears.

If you were to put your ear close to a train track, as shown in Figure 1.16, you might hear a train coming long before you could see it. When a train moves, its vibration is transmitted to the rails through the wheels, and the waves generated by this vibration are transmitted through the structure of the rails. Then the waves in the structure radiate into the air as sound that you can hear. Because the propagation speed of sound waves in the solid rails is much faster than in the air, you can hear the train long before you see it.

There are many transfer paths for structural-borne sound inside the vehicle. For example, engine vibration is transmitted to the subframe, then the vibration waves are transmitted inside the body frames and reach the body panels; finally, the excited panels radiate sound to the interior. This radiated sound is the structural-borne sound. Below are examples of structural-borne sound transmitted in the vehicle.

- Power plant vibration is transmitted to the body through mounting systems, and then the excited panels radiate sound to the interior.
- Exhaust vibration is transmitted to the body through hangers, and then the excited panels radiate sound to the interior.
- Driveshaft vibration is transmitted to the body through bearing supports, and then the excited panels radiate sound to the interior.
- Road excitation is transmitted to the body through the suspension, and then the excited panels radiate sound to the interior.

1.2.3 Transfer of Noise and Vibration Sources to Interior

Noise and vibration sources are outside the body, and the occupants sit in the vehicle and perceive the noise and vibration, so the body is a barrier between the sources and the occupants. In the analysis of vehicle noise and vibration, the source–transfer path–receiver model shown in Figure 1.13 is used. So the body is the transfer path of noise and vibration transmission, whereas the receivers are the occupants who perceive the noise and vibration.

According to the definitions of airborne noise and structural-borne noise, the model expressed in Figure 1.13 can be extended, as shown in Figure 1.17. Figure 1.17 shows the sources of airborne noise and structural-borne noise and the corresponding transfer paths.

The interior noise and vibration are determined by the outside sources and transfer paths, and can be expressed by the following equation:

$$NV = \sum_{i=1}^{N} S_i H_i, \tag{1.1}$$

where NV represents the interior noise or vibration, S_i is i^{th} noise source or vibration source outside the vehicle, and H_i is the i^{th} noise or vibration transfer path.

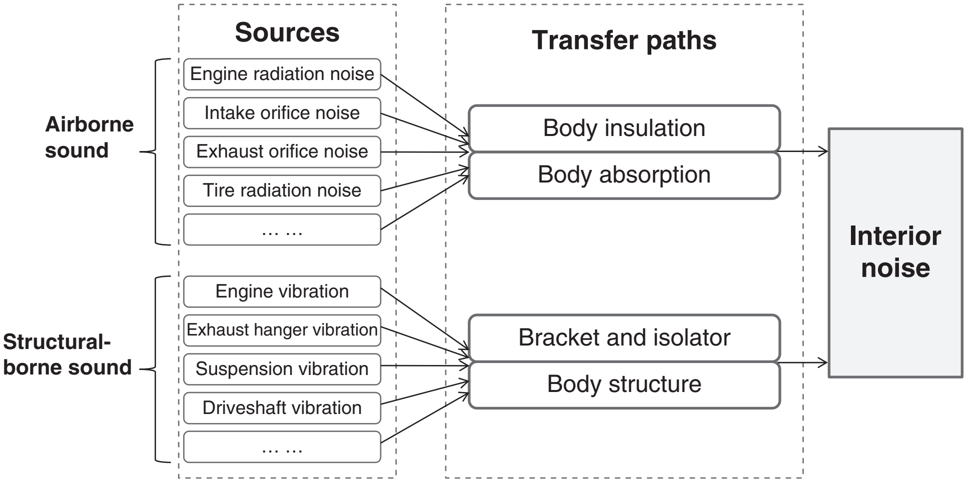


Figure 1.17 Sources and body transfer paths of airborne noise and structural-borne noise.

From Eq. (1.1), it can be seen that the interior noise and vibration can be controlled from two aspects: source and transfer path. Chapter 5 describes the characteristics of major sources in detail. After understanding the characteristics, engineers can control the noise and vibration sources. The characteristics of the airborne and structural-borne transfer paths are briefly described as follows.

For airborne noise, the transfer path is the body sound insulation and sound absorption layers. The sound source is transmitted to the body, some sound waves are reflected, some are absorbed, and the rest pass through the body and enter the interior. The performance of the body sound insulation and absorption is represented by sound–sound transfer function, which means attenuation of the outside sound transmitted into the interior. The higher the sound–sound transfer function, the greater the sound attenuation.

For structural-borne noise, the transfer path refers to the transmission of vibration at a body point to sound in the interior. The performance of the structural-borne sound can be represented by sound–vibration transfer function, which means the interior sound generated by unit force applied on a point. Compared with the airborne noise transfer path, the structural-borne transfer path is more complex. For example, to examine the transfer paths of the engine mountings, three factors must be analyzed: first, the stiffness and modes of mounting brackets; second, the dynamic stiffness of the connected points between the body and the mountings; and third, the interior noise generated by applying force at the connected points.

One of the most important areas of vehicle NVH research is analysis of the characteristics of the transfer paths, and the discovery of methods to control the transfer paths. In this chapter and the following chapters, I focus on how to design the transfer paths to attenuate the transmission of outside noise and vibration sources to the interior.

1.3 Key Techniques for Body Noise and Vibration Control

The frame structure determines the overall modes of the body, and the panel structure determines the noise radiation and its coupling with the cavity mode. The body is the noise and vibration transfer path, and it can be divided into airborne and structural-borne transfer paths, which are related to the body's acoustic sensitivity and vibration sensitivity, respectively. In some special circumstances, the body could have special problems, such as high-speed wind noise, door closing sound quality, or S&R. The development of the body is based on a target system, so clear targets are the key to achieving a successful body development. The key techniques for body NVH control can be categorized as follows:

- vibration and control of overall body structures
- vibration and sound radiation of body local structures
- sound package
- body noise and vibration sensitivity
- wind noise and control
- door closing sound quality and control
- S&R of vehicle body.

In this book, the above seven aspects are covered from Chapter 2 to Chapter 8, respectively. The following sections briefly describe the seven aspects.

1.3.1 Vibration and Control of Overall Body Structure

Controlling the vibration of the overall body structure means controlling the body stiffness and mode from the perspective of the body frame structure in order to achieve good noise and vibration performance. The main research areas include:

- Control of overall body stiffness
- Identification of overall body mode
- Control of overall body mode.

1.3.1.1 Control of Overall Body Stiffness

The stiffness is the basis of the body. Insufficient stiffness brings not only NVH problems such as vehicle shake, interior booming, and S&R, but also safety and reliability problems. The research scope of body stiffness includes measurement, analysis, and control of body stiffness.

Stiffness is divided into bending stiffness and torsional stiffness. Bending stiffness refers to the body's capacity to resist bending deformation under the action of an external force. The connection points between the front shock absorbers and the body and the rear shock absorbers and the body are constrained, and a concentrated force is applied at the installation location of the rear seats. The applied force is divided by the maximum deformation to obtain the body's bending stiffness.

When the loads applied on both sides of the vehicle are different, the body is twisted, resulting in torsional deformation. Torsional stiffness refers to the body's capability to resist torsional deformation. The connection points between the rear shock absorbers and the body are constrained, and a torque is applied at the connection points between the body and the front shock absorbers. The body torsional stiffness is obtained by dividing the torsional angle by the torque.

Using the above boundary conditions and loads, the body's bending stiffness and torsional stiffness can be obtained by testing or by computer aided engineering (CAE) analysis.

Factors affecting the overall body stiffness include the layout of the overall frame, the frame cross-section, and joint stiffness. The overall layout refers to the arrangement of the frames, cross members, and pillars, which must form closed loops. The frame's stiffness depends on its cross-section. The bending stiffness depends on the moment of inertia of the section, and the torsional stiffness depends on the polar moment of inertia of the section. The moment of inertia and the polar moment of inertia of a closed-loop section are much larger than those of an open-loop section, so the frame sections should be designed as closed loops wherever possible. The joint stiffness is defined as the local stiffness at the intersections of the frames, pillars, etc.

High body stiffness can only be achieved through rational layout of the body frame structure, a cross-section with large moment of inertia, and high joint stiffness. When analyzing body stiffness, all three factors must be simultaneously considered.

1.3.1.2 Identification of Overall Body Mode

Vehicle body mode identification involves obtaining the modal frequencies and mode shapes of the vehicle body by testing or analyzing, and then determining the factors that affect the modal characteristics. The most important body modes are the first bending mode and the first torsional mode.

Accelerometers are placed on particular points of the body, and exciters are used to vibrate high-stiffness locations (such as the connection point between a shock absorber and the body). After the excitation signals and responses have been processed, the transfer functions between the outputs and the inputs can be obtained and the modal parameters are extracted. The body modal analysis is usually implemented by finite element (FE) analysis. After the body is discretized into a number of finite grids, and the excitation points and the response points are chosen, the accelerations and forces are calculated, and the transfer functions and modal parameters can be obtained.

In body testing and analysis, the BIW is the most important because it is the most basic structure. After the windshields, seats, doors, and other trimmed structures are added onto the BIW, the body weight increases, and its stiffness changes. Under normal circumstances, the modal frequency of the bending mode of the trimmed body is much lower than that of the BIW. The trimmed parts greatly increase the torsional stiffness of the trimmed body, but although the body weight increases, the torsional modal frequency changes little compared with that of the BIW. The modal frequencies of the BIW, the trimmed body, and the whole vehicle body are related, so after the modal frequency of the BIW has been obtained, the modal frequencies of the trimmed body and whole vehicle body can be roughly calculated.

Modal identification also involves determining the nodes of the dominant modes. The lump masses of the external systems should be placed on the nodes or as close to them as possible so that the systems' influence on the body's modes or the influence of external inputs on the body can be minimized.

1.3.1.3 Control of Overall Body Mode

Control of the overall body mode refers to methods to control the body modes by decoupling systems and excitation, decoupling modes of adjacent systems, and establishing modal tables. Overall body mode control involves three aspects: first, the modal frequency and excitation of each system is analyzed so that adjacent systems can be decoupled from each other and from external excitation; second, a complete mode distribution table is developed; and third, modal decoupling and noise and vibration suppression is achieved by adjusting the stiffness, mass, and structure distribution of the vehicle's systems.

The first task of mode control is to determine the associated systems and their coupling status: i.e. to determine the principles of modal separation and decoupling. Decoupling involves three aspects: decoupling of the overall body modal frequency and the external excitation frequency, decoupling of the overall body modes and the modes of the systems connected with the body, and decoupling of the overall body modes and the local modes.

The second task of mode control is to develop a modal distribution table. After the excitation frequencies, the modal frequencies of the overall body, and the frequencies of the connected systems have been determined, a modal table can be established. This means that the modal frequencies of each system can be planned, which can guide the development of each system.

There are three body modal planning tables. The first is the whole-vehicle modal planning table, in which the modal frequencies of the body and each system are listed in a table. The purpose of the table is to indicate whether each system can be decoupled and to show whether they are separated from the idle excitation frequencies. After the whole-vehicle modal planning table has been determined, the modal frequency targets of each system can be determined, so the development of each system can be relatively independent. The second table is the body modal frequency table, in which the modal frequencies of the overall body and each system/component connected to the body are put together. The purpose of this table is to decouple the overall body modes and the local body modes, and to separate the modal frequencies from excitation frequencies. The third table is the excitation frequency and body mode table, in which the excitation frequencies and the body modal frequencies are placed in a chart or table to illustrate the relationships among body modal frequency, excitation frequency, engine speed, order, and so on. The third table and second table can be used simultaneously, so the relationship between the body mode frequency and excitation can be quickly diagnosed.

The third task of modal control is to separate and control the body modes by modifying the body structure. The overall body mode is mainly determined by the body's stiffness and mass distribution, so the body mode can be altered from two aspects. In addition, some systems connected to the body can be regarded as dynamic vibration dampers that can adjust the body's response at certain modal frequencies. The first body bending mode and first torsional mode should be designed to be as high as possible and far away from the frequencies of the main excitation sources. If a body modal frequency and an excitation frequency are unavoidably overlapped, the excitation should be placed as close as possible to the modal nodes.

1.3.2 Vibration and Sound Radiation of Body Local Structures

The frame structure is the foundation of the vehicle body, and the panels and accessories are connected to the frame structure by welding, riveting, etc. The body local structure has two categories: panels and accessories. Panels are metal sheets covering the frame, such as the dash panel, roof, floor, side panels, doors, engine hood, and trunk lid, which are connected to the frame by welding or other means to form an enclosed body. Accessories are the components installed on the body, such as the steering system, instrument panel, interior rearview mirror, and exterior side mirrors.

A panel is a thin-walled plate. After being excited, it easily radiates noise. The enclosed air inside the body forms a cavity with an acoustic cavity mode. The modal frequency of the panel is relatively low, so its structural mode can easily couple with the acoustic cavity mode, generating interior booming. Many accessories are directly related to the occupants' perceptions. The noise and vibration produced by panels and accessories, such as steering wheel vibration and mirror shake, can be directly perceived by the occupants.

Controlling the vibration and noise of local structures involves the following aspects:

- Control of panel vibration and sound radiation
- Acoustic cavity modes
- Control of accessory vibration.

1.3.2.1 Panel Vibration and Sound Radiation

A panel is like a drum membrane. When the membrane is beaten, its surface vibrates like a ripple across water, as shown in Figure 1.18. Likewise, when a body panel is excited, the vibration wave forms a layered pattern that expands from its center to the edge.

When the panel modal frequency and the external excitation frequency are the same or close to each other, the panel is easily excited and radiates noise to the interior. For example, when vibration from the suspension system is transmitted to the floor, the floor is excited and radiates noise into interior. Another example is the air conditioning tube passing through the dash panel: the engine vibration will be transmitted to the dash panel through the tube, and then the excited panel radiates sound.

The primary task of panel structure research is to establish the relationship between the panel mode and the excitation. The main body panel modes include the dash panel mode, roof mode, floor mode, hood mode, and trunk lid mode. Almost all the excitation sources are likely to excite the panels, so it is necessary to determine the source frequencies and establish a modal planning table that includes the panel modal frequencies and the excitation frequencies. From the table, the modal coupling relationships between the panel modes and the excitations can be clearly discerned, and attempts can be made to decouple them. In addition, adjacent panels should have different modal frequencies, and the panel modes should also be different from the cavity modes.

The second task of panel structure research is to study the vibration characteristics of panels. Body panels are too complex for the use of analytical methods in solving vibration problems. In engineering, the structural modes and vibration responses of body panels are acquired by testing and/or numerical calculation methods. However, some body panels can be simplified as a basic supported plate to allow the use of an analytical method.

The third task of panel structure research is to study the acoustic radiation characteristics of panels. Panel vibration brings two types of noise problems: first, panel vibration can directly radiate noise to the interior, and second, an interior booming noise can be generating by coupling between the panel mode and the cavity acoustic mode. The sound level of the direct radiation is given as the radiated sound power (W_{rad}), and expressed as

$$W_{rad} = \sigma \rho_0 c S \langle \bar{u}^2 \rangle, \tag{1.2}$$

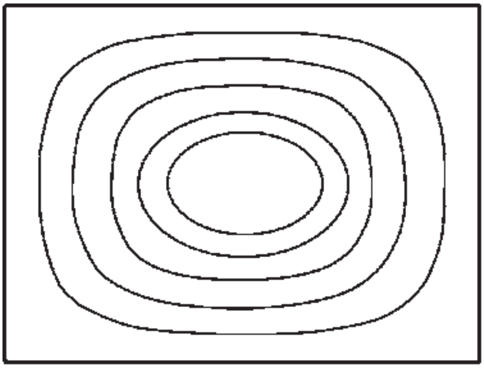


Figure 1.18 Structural wave pattern of a vibrated panel: first mode.

where σ is the sound radiation coefficient, ρ_0 is the air density, c is the sound speed, S is the panel area, and $\langle \bar{u}^2 \rangle$ is the square of the average sound speed.

The study of panel sound radiation includes the radiation mechanism of the panel structure, sound radiation efficiency, and analysis of the contribution of each panel to sound radiation. Studying the radiation mechanism involves analyzing the characteristics of bending wave propagation inside the panel, including the wave pattern, speed, and frequency, and finding the sound radiation process of the bending waves to the interior. The radiation capacity of the bending waves depends on their frequencies. The bending wave frequencies can only radiate sound when they are higher than a critical frequency. According to Eq. (1.2), the radiated sound power is proportional to the square of the panel vibration speed. The panel radiation efficiency represents its radiation capacity: i.e. sound energy radiated to the air per unit of time. The greater the radiated sound energy, the higher the efficiency. Panel radiation contribution analysis involves determining the ratio of the interior sound pressure contributed by each panel to that contributed by the panels overall in order to find the main panels that contribute to the interior sound.

The fourth task of panel structure research is to control panel vibration and sound radiation, which can be done by adjusting the stiffness, damping, and weight of local panels, and by using vibration dampers.

The panel stiffness perpendicular to the panel determines its modal frequencies. For a panel with low frequency, the best method to increase its frequency is to add support onto its surface. For example, the frequencies of most dash panels are between 50 and 150 Hz, and a dash panel can be excited by components that pass through it, such as the steering shaft, air conditioning tubes and clutch cable. The excitation frequencies may be coupled with the panel frequency. To separate this coupling, the panel structure must be modified. There are several ways to reinforce the panel: the first way is to punch a flat panel to form a beaded panel, the second is to force the flat panel in several different planes, and the third is to weld supporting beams onto the panel or to coat it with reinforcement adhesives. In some locations where it is hard to place supporting beams, reinforcement adhesives can be used, such as the adhesive used on outer door panels. Figure 1.19 shows a flat panel and a bead panel of the same size; the frequency of the bead panel is much higher than that of the flat panel.

When supporting beams cannot be used to reinforce a panel's stiffness, damping treatment is the most commonly used method to suppress panel vibration and sound radiation. Damping material is pasted onto the panel surface, a sandwiched damping

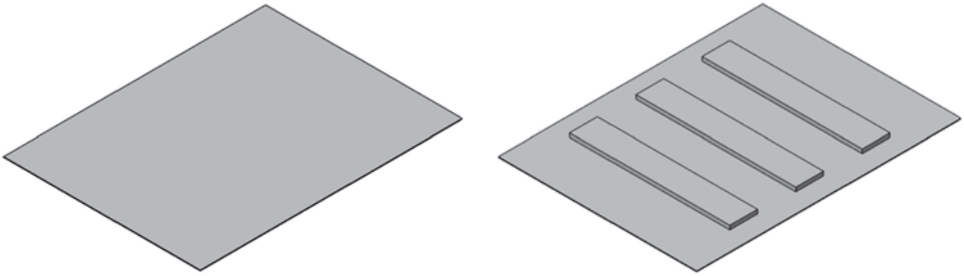


Figure 1.19 Flat plate and bead plate.

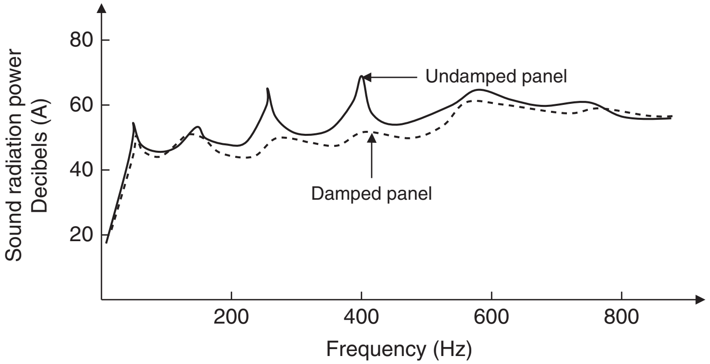


Figure 1.20 Comparison of magnitude of sound radiation of an undamped panel and a damped panel.

structure is installed on the panel, or a multi-layer damping plate is used directly. Figure 1.20 shows a comparison of the magnitude of the sound radiation of an undamped panel and a damped panel.

There are three methods of damping treatment: free damping, constrained damping, and laminated steel. In free damping, the damping material is directly pasted onto the surface of a panel, such as the floor, wheelhouse, or luggage compartment, to attenuate the road noise. In constrained damping, a damping layer is sandwiched between a body panel and a constrained metal sheet to form a "sandwich" structure: for example, a sandwiched panel used on the rear wheelhouse can attenuate noise from the road and splashing water. Laminated steel is an independent "sandwiched" damping panel that is also a form of constrained damping. In some vehicles, laminated steel is for the dash panel.

Damping material is used where the strain energy of the panel structure is at maximum. Damping treatment usually aims to suppress vibration and sound radiation at middle frequencies (200–500 Hz), especially at resonant frequencies. Usually, the damping treatment is also associated with the sound package to improve the sound transmission loss (STL). In some cases, damping is also effective at high frequencies (above 1000 Hz).

Mass can also be used to adjust the panel modal frequency. A mass block (also called a mass damper) can be regarded as a special dynamic damper. After being placed on a panel surface, the mass block can not only change the panel's frequency, but also suppresses its vibration magnitude. Mass dampers are widely used to attenuate interior booming by placing them on a problem panel. First, the panel that has the same frequency as the interior booming frequency is identified, then its mode is analyzed or measured, and finally the optimal location for the damper is determined. However, compared with the stiffness control method, the dynamic tuning range of the mass damper is narrow.

A dynamic damper is an additional mass-spring system that is added onto the panel structure to suppress its vibration at a certain frequency. After identifying the panel structure radiating noise and its frequency, an additional mass-spring system with the same frequency of the panel structure is designed. The mass-spring system suppresses the panel vibration and sound radiation, and reduces booming.

1.3.2.2 Acoustic Cavity Mode

The air inside the body forms an enclosed cavity. The enclosed air is similar to a solid structure and has its own mode. The mode formed by the enclosed air is called the acoustic cavity mode. The mode distribution of the structure is characterized by displacement, whereas the mode distribution of the enclosed air is described by pressure. Figure 1.21 shows the first acoustic cavity mode of a vehicle body.

The modal shapes and frequencies of the acoustic cavity modes are determined by the interior space and the medium, whereas the space depends on the styling and interior design. When the styling is finalized, it is almost impossible to change the cavity modes and frequencies. The frequencies of the cavity modes are relatively low: for example, the first modal frequency for a sedan is between 40 and 60 Hz, and the modal shape (sound pressure) varies along the longitudinal direction of the vehicle body. The pressures are large in some locations, but small in others. The shape looks like an accordion, as shown in Figure 1.21. Similar to the first modal shape, the second modal shape also changes along the longitudinal direction. The third modal shape changes along the lateral direction of the vehicle body, and the high-order modal shapes are more complicated.

The acoustic cavity modes usually bring two kinds of noise problems. The first problem is the modal coupling motion between the acoustic cavity mode and the body panel mode. Excited by an external excitation, the body panel pushes against the cavity. The panel acts like loudspeaker membrane, generating sound. This tiny sound is amplified inside the acoustic cavity mode, inducing a booming when the modal frequencies of the panel and the cavity are the same. The second problem occurs when the frequency of an external noise source, such as an exhaust orifice noise, is coupled with the frequency of the acoustic cavity mode, generating interior booming.

Acoustic cavity mode studies involve three aspects. The first is studying the characteristics of the cavity modal frequencies and shapes, including the measurement and analysis of acoustic cavity modes. The second is studying the coupling relationship between the panel structural modes and acoustic cavity modes, and finding methods to decouple them. The third is studying the influence of the acoustic modes on the sound–sound transfer function: i.e. the relationship between the external sound excitations and the acoustic cavity modes. The mode that induces interior booming is often the first

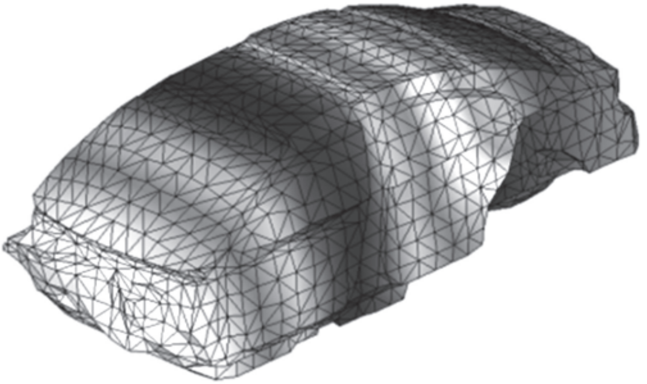


Figure 1.21 First acoustic cavity mode of a vehicle body.

one, so the key focus of these studies is controlling the first cavity mode and finding methods to avoid its excitement.

1.3.2.3 Control of Accessories

Many components, such as the steering system, mirrors, and so on, are installed on the body. If they are inappropriately designed, they can produce noise and vibration problems, such as a steering wheel “nibble” (oscillation at cruising speeds) or shaking mirrors. From the NVH point of view, the accessory structures are divided into three categories: bracket, steering system, and seat.

A bracket, such as a bracket connecting the engine to the body or a hanger connecting the exhaust system to the body, is a bridge between the body and a system. Figure 1.22 shows a bracket (a), and a bracket connecting with an engine mounting (b). The bracket is the transfer path of the external noise and vibration sources to the body, and often brings noise and vibration problems. A bracket with a low modal frequency is easily excited, and a vibration source easily passes along the transfer path and reaches to the body; in addition, the bracket easily radiates sound. For example, a mounting bracket with 300 Hz modal frequency is subjected to excitation from a four-cylinder engine at 4500 rpm; because the fourth-order excitation frequency corresponding to the speed is 300 Hz, the bracket resonates and transmits the engine vibration to the vehicle body, and could induce interior sound resonance. A bracket and its connected system constitute a mass-spring system; when the system frequency is consistent with the external excitation frequency, it resonates. For example, the mass-spring system of a battery and its holder has a relatively low frequency, so the holder is easily excited by the road excitation and the vibration is transmitted to the vehicle body via the bracket.

The bracket can be regarded as an extension of the body. The body structural characteristics should be included in the bracket design, and one principle of bracket design is that no resonance is induced for the bracket. The bracket should be as short as possible

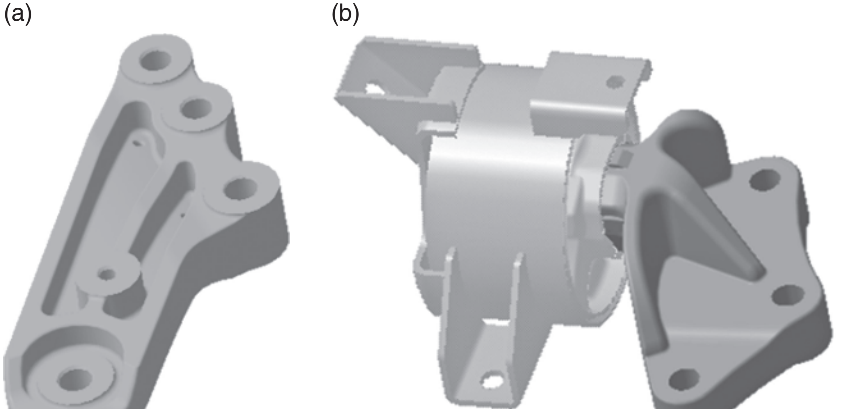


Figure 1.22 Engine mounting brackets. (a) A bracket. (b) A bracket connected with an engine mounting.

so that its frequency is high enough to avoid the excitation frequency, and it must be installed at a body location with high dynamic stiffness.

The steering system is composed of the steering shaft system and CCB system, as shown in Figure 1.23, and the steering wheel is mounted on the steering shaft. Because the steering system is connected to the body, the vibration transmitted to the vehicle body is likely to be transmitted to the steering wheel. There are three typical vibrations on the steering wheel that the driver can perceive: vibration at idling, shake during acceleration, and nibble at cruising. The principle way to avoid these problems is to keep the frequency of the steering system away from the external excitation frequency; therefore, the frequency of the steering system is usually designed to be as high as possible. The general rule is that the frequency should be at least 3 Hz higher than the excitation frequency. For example, the speed of a four-cylinder engine at idle and with the air conditioning on is 900 rpm, and the corresponding second-order frequency is 30 Hz, while the cooling fan speed is 1900 rpm and the corresponding first-order dynamic unbalance frequency is 31.7 Hz, so the steering system frequency must be designed to be 35 Hz or higher.

The frequency of the steering system depends on the frequency of the steering shaft system and the frequency of the CCB system. The frequency of the steering shaft system is determined by the stiffness of the shaft, the positions of the supporting points, the stiffness of the supporting brackets, and the weight of the steering wheel and the airbag. The stiffness of the CCB system is determined by the beam stiffness, the connection between the beam and the A-pillars, the supporting points on the beam, and the stiffness of the supporting brackets. The frequency of the steering system can only be increased if the frequencies of both the steering shaft system and the CCB system are enhanced.

The seat is composed of a seat frame, cushion, and backrest. The frame acts as a support, so it must have sufficient stiffness to separate the seat modal frequencies from the excitation frequencies of the engine and road, and also to avoid resonance. The cushion and backrest are in direct contact with the occupants, affecting their ride comfort, so their frequencies must be kept away from frequencies that are sensitive to the human body in both the vertical and lateral directions.

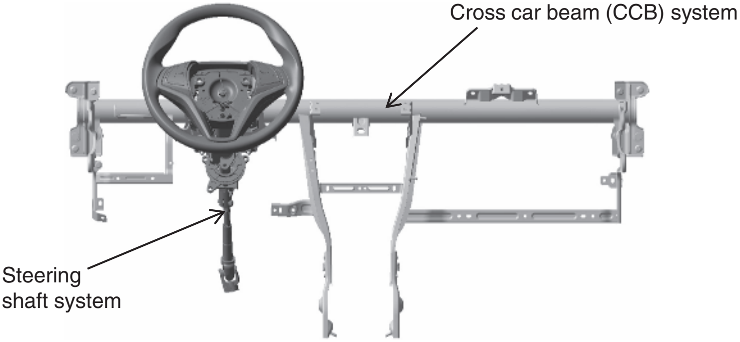


Figure 1.23 Diagram of a steering system.

1.3.3 Sound Package for Vehicle Body

Interior trimming, including sound absorption and insulation materials, is installed on the BIW not only to decorate the interior but also to absorb and insulate noise. Conventionally, non-metallic materials, structures, and techniques associated with acoustical treatment in the vehicle body are referred to as the sound package.

An index to evaluate the effect of the sound package is noise attenuation (NR). It is defined as the difference between the sound pressure level (SPL_{out}) of the outside sound source and the SPL_{in} inside the vehicle, and is expressed as

$$NR = SPL_{out} - SPL_{in}. \tag{1.3}$$

A sound simulator is placed outside the vehicle, and then sound pressures in vicinity of the simulator and inside the body are measured simultaneously. Finally, the NR is obtained by subtracting the sound pressures. For example, to measure the attenuation of engine noise transmitted into the interior, an engine noise simulator is placed in the engine compartment, whereas to measure the attenuation of exhaust orifice noise transmitted into the interior, an exhaust noise simulator is placed near to the exhaust orifice.

In general, the NR increases with frequency increase at a 6 dB/octave slope, as shown in Figure 1.24. The greater the NR, the better the sound insulation effect. For vehicles with a good acoustic package, the NR should be 35–40 dB at 1000 Hz.

Under normal circumstances, the sound package refers to the "special" sound package, including body sealing, sound absorptive materials and structures, and sound insulation materials and structures. The "general" sound package represents a combination of the "special" sound package with damping materials and structures and reinforcement materials and structures. Usually, the damping materials and structures are described in the study of panel vibration.

1.3.3.1 Body Sealing

No matter how good the body is, and no matter how many sound insulation and sound absorptive materials are used, if there are apertures on the body, outside noise will

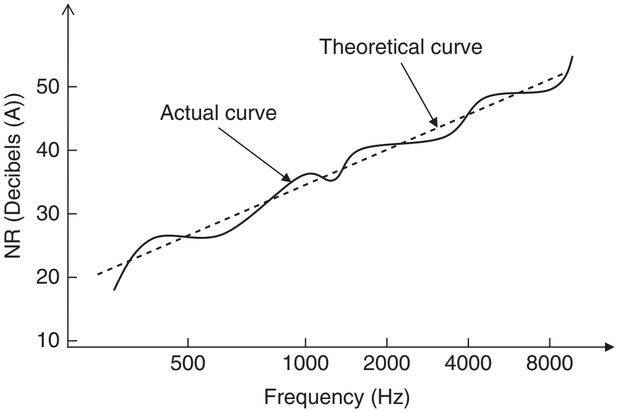


Figure 1.24 Noise reduction (NR) increases with frequency increase.

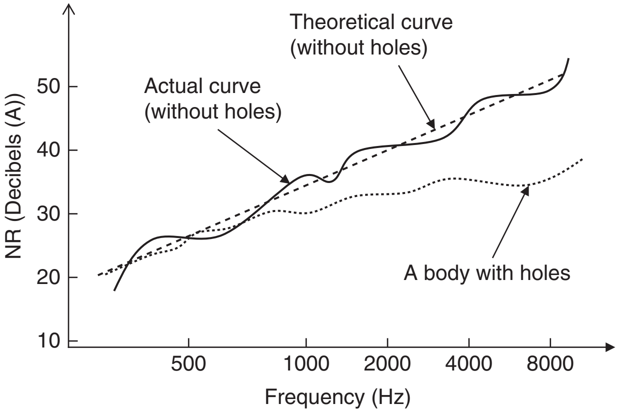


Figure 1.25 Noise reduction (NR) comparison of an ideal body without holes and a body with holes.

directly pass through these holes and enter the interior. Figure 1.25 shows an NR comparison between an ideal body without holes and a body with holes. The apertures significantly reduce the body NR, especially at high frequencies. Therefore, the most basic work of the sound package is to achieve a good body sealing.

Body sealing is divided into static sealing and dynamic sealing. Static sealing refers to body sealing when the vehicle is at a standstill; dynamic sealing refers to body sealing when the vehicle is running. When the vehicle moves, some components could have relative movement (such as the doors and body frame). Good static sealing does not guarantee good dynamic sealing.

The apertures, or holes, on the body are divided into three categories: function holes, manufacturing process holes, and error-state holes. Function holes are those that are deliberately opened on the body panels to realize some designed functions. For example, there are many holes on a dash panel (as shown in Figure 1.26) to allow the steering shaft, air-conditioning tube, shift cable, and so on to pass through it. Manufacturing process holes are opened for certain manufacturing processes and then sealed after the processes are finished. For example, during electrophoresis, the BIW is immersed in an electrophoresis fluid tank; after the process is finished, the liquid must be drained out of the body through holes. Error-state holes are generated by design error and/or manufacturing error. They do not have a function and are not needed for any manufacturing process.

Static sealing measurement methods include the smog method, ultrasound method, and air leakage method. In the smog method, a smoke generator is placed inside the vehicle and releases smoke that penetrates the holes on the body and diffuses to the outside. People standing outside the vehicle observe the smoke and judge the locations and sizes of the holes according to the amount of leaked smoke. In the ultrasound method, an ultrasonic leak detector system is used to send and receive ultrasonic waves. The waves are emitted by a generator inside a vehicle and are detected by a receiver outside the vehicle if there are holes in the body. The characteristics of the ultrasound waves allow the quantity and location of leakage to be easily read on the receiver screen. In the air leakage method, air is blown into the body. When the blower stops, air will flow out of the body if it contains holes, and the pressure inside the body will drop.

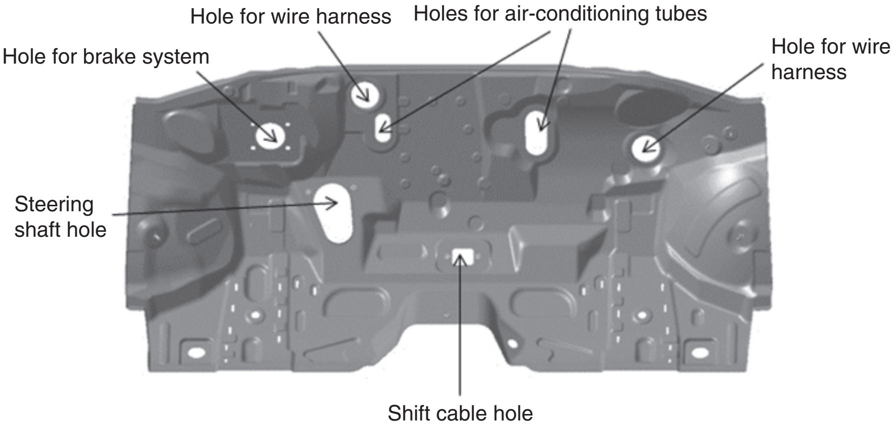


Figure 1.26 Apertures/holes on a dash panel.

The air leakage method uses the principle of the flow pressure difference inside and outside the vehicle to measure the body leakage.

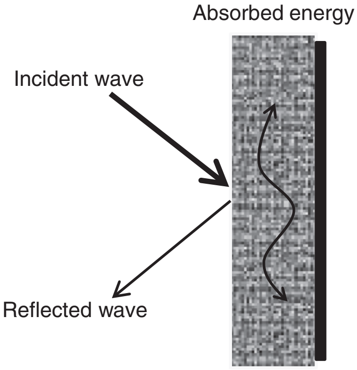


Figure 1.27 Reflection and absorption of a sound wave.

1.3.3.2 Sound Absorptive Material

When sound waves are transmitted to the surface of a sound absorptive material, some of the energy is reflected back and some is absorbed and converted into heat, as shown in Figure 1.27. It is assumed that sound waves are only reflected and absorbed, and are not transmitted. The sound absorption capacity of the material is represented by the sound absorption coefficient. Figure 1.28 shows the sound absorption coefficients versus frequency for three types of sound absorptive materials. The coefficients increase with the increase in frequency. The coefficients are relatively low at a low-frequency range, are high at the high-frequency range, and then trend to becoming stable after a certain frequency. The material's sound absorption coefficient can be measured inside an impedance tube or reverberation chamber.

Sound absorptive material is soft and porous. Factors affecting the material's sound absorption performance include flow resistance, porosity, structural factor, density, and thickness. The flow resistance represents the material's permeability. The higher the flow resistance, the worse the material's permeability. The material's flow resistance should be controlled within an appropriate range. The porosity is the ratio of the volume of air in the material to the total volume of the material, which reflects the density of the material. The sound absorption coefficient increases as the density of the material increases. But after the density increases to a certain value, the porosity decreases and the flow resistance increases, so its sound absorption performance increases at a low-frequency range, but decreases at a high-frequency range. Therefore, each material should have a suitable density. The structural factor is a dimensionless parameter that reflects the internal shape and arrangement of the material. Structural factors have little

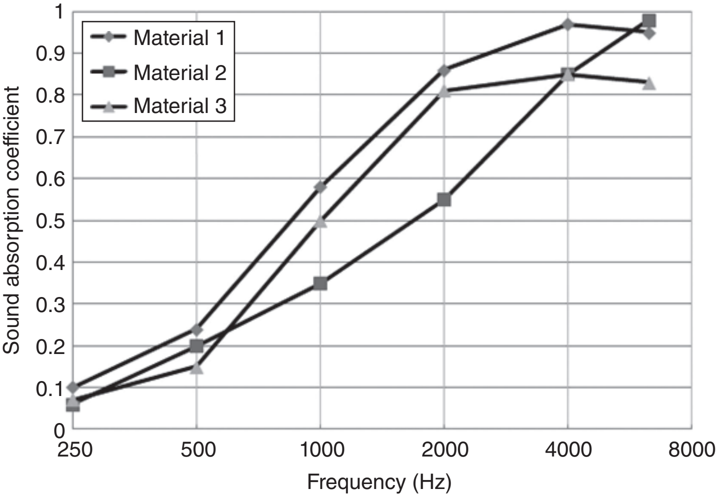


Figure 1.28 Sound absorption coefficients versus frequency for the three types of sound absorptive materials.

impact on the low-frequency sound absorption performance of the material, but have significant influence on the high-frequency absorption performance. The sound absorption coefficient increases as the thickness of the material increases, especially in the low-frequency range, but when the thickness increases to a certain value, the relative increase in the sound absorption coefficient begins to drop.

The porous sound absorptive materials used in vehicles mainly fall under three categories: cotton felt, foam, and glass fiber. Cotton felt is cheap and widely used in economy vehicles. Foam has good sound absorption effects and is widely used in mid-range and luxury vehicles. Glass fiber has good thermal insulation and moisture-proofing effects, so it is often used as a hoodliner and sound insulator inside the engine compartment.

Sound absorptive materials are widely used in automotive interior parts, such as the hoodliner, dash insulator, roof lining, and so on. Sound absorptive materials are also freely placed inside A/B/C-pillars, rockers, door trims, wheelhouses, instrument panels, and so on.

1.3.3.3 Sound Insulation Material and Structure

When sound waves are transmitted to the surface of a sound insulation material, some waves are reflected back, some are absorbed by the material and converted to heat, and some continue to pass through the material, as shown in Figure 1.29. The effect of sound insulation is measured by the amount of STL. There are two ways to measure STL: via an impedance tube or in a special laboratory that combines a reverberation chamber and an anechoic chamber.

Sound insulation structures include single-plates and double-plates. The sound insulation performance of a single-plate is determined by its density (or mass), stiffness, and damping. At a low-frequency range, the sound insulation effect is controlled by the stiffness. Above a certain frequency, the sound insulation is determined by its mass, and increases by 6 dB when the mass is doubled. In this region, the sound insulation increases with frequency, and when the frequency is doubled, the sound insulation

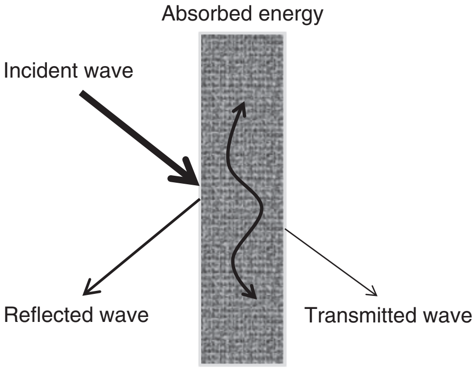


Figure 1.29 Reflection, absorption, and transmission of a sound wave.

Figure 1.30 Relationship between a system and input and output.

increases by 6 dB. At a high-frequency range, coincidence occurs. When the frequency approaches the coincident frequency, the sound insulation decreases rapidly and is also affected by the structural damping. However, double-plate overcomes the shortcomings of single-plates. The double-plate structure has a good sound insulation effect at high frequencies, so it is used in some critical locations on the vehicle, such as the front windshield.

The body panels and glass are sound insulation structures. Sound insulation material is rarely used alone; instead, it is usually combined with sound absorptive materials. For example, the dash insulator is combination of sound insulation and sound absorptive materials.

1.3.4 Body Noise and Vibration Sensitivity

1.3.4.1 Transfer Function and Sensitivity

When an input excitation is applied to a system, an output response is generated, as shown in Figure 1.30. The ratio of the output response to the input excitation is called the transfer function, and is expressed as

$$H(\omega)=\frac{Y(\omega)}{X(\omega)}, \tag{1.4}$$

where $X(\omega)$ and $Y(\omega)$ are the input function and output function, respectively.

The body is a system in which the external noise and vibration sources exerted on the body are inputs, and the interior noise and vibration are responses. For example, when a mounting point between the power plant and body is impacted and exerts a vibration on the body, the generated interior noise and the vibration on the steering wheel are the outputs. The ratio of the interior noise to the vibration on the mounting point is called the sound–vibration transfer function, whereas the ratio of the vibration on the steering wheel to the vibration on the mounting point is called the vibration–vibration transfer function.

In body noise and vibration analysis, the word "sensitivity" is often used. Sensitivity refers to how sensitive the output response is to the input excitation in a system. In fact, sensitivity is the transfer function, but in the automotive NVH world, engineers prefer to use the word sensitivity to emphasize the sensitivity of the output to the input. For example, for vehicle A, a 1 N force is applied to a mounting point and 55 dB (A) of interior sound is generated, so the sound–vibration sensitivity is 55 dB N^{-1}; whereas for vehicle B, a 1 N force is exerted on the same mounting point and 60 dB (A) of interior sound is generated, so the sensitivity is 60 dB N^{-1}. Therefore, we can say that the sound inside vehicle B is more sensitive than that of vehicle A for the same force input.

The sensitivity reflects the characteristics of a system. For a linear system, the sensitivity is independent of the input and output; however, for a nonlinear system, the sensitivity not only relates to the system, but also depends on the input and output. There are many nonlinear systems on a vehicle, such as the seats. The sensitivity between seat cushion vibration (output) and seat rail vibration (input) varies with the magnitude of the external excitation. Strictly speaking, the body is a nonlinear system, but in engineering, the body can be approximately regarded as a linear system.

Body sensitivity is divided into two groups: structural sensitivity and acoustic sensitivity. Structural sensitivity can be further divided into sound–vibration sensitivity, vibration–vibration sensitivity, and driving point dynamic stiffness.

1.3.4.2 Structural Sensitivity

Structural sensitivity reflects the influence of body vibration on interior noise and vibration: i.e. the sensitivity of the interior noise and vibration caused by applying force or vibration excitation on the body. Many points on the body are subjected to external excitations, such as the mounting points where the engine applies force to the body, the connecting points between the exhaust system and the body, the connecting points between the shock absorbers and springs and the body, and the connecting points of the driveshaft bearings.

Sound–vibration sensitivity is the ratio of the interior noise to a unit of excitation force and is expressed as (P/F), where P represents the interior sound pressure and F represents the force exerted on the body.

The severity of vibration on the steering wheel, seat, and floor generated by a unit of force is described by vibration–vibration sensitivity. This is defined as the ratio of vehicle vibration to a unit of excitation force and is expressed by (V/F), where V represents the vibration inside the vehicle and F is the force exerted on the body.

Structural sensitivity represents the transmission of structural-borne sound to the interior. Figure 1.31 shows the transfer processes of sound–vibration sensitivity and vibration–vibration sensitivity.

Control of sound–vibration and vibration–vibration sensitivities is key to controlling structural-borne sound transmission. The two sensitivities should be controlled within certain ranges: for example, generally, the sound–vibration sensitivity should be less than 55 dB N^{-1}.

Dynamic stiffness refers to the ratio of an excitation force to the displacement response and is a function of frequency. If the excitation force and the response are at same point, the dynamic stiffness is called driving point dynamic stiffness, and the point is called the driving point. Driving point dynamic stiffness reflects the strength

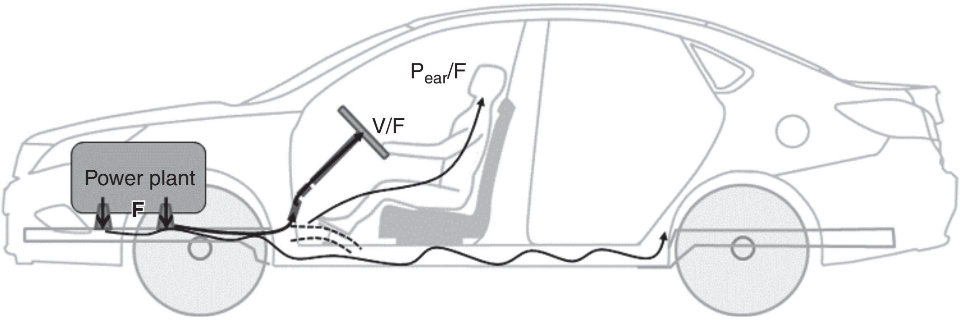


Figure 1.31 Transfer processes of sound–vibration sensitivity and vibration–vibration sensitivity.

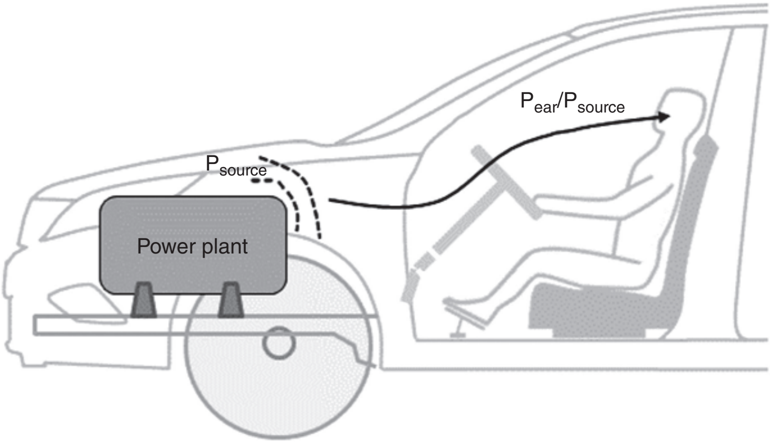


Figure 1.32 Transfer process of acoustic sensitivity.

of the structure at this point. The lower the driving point dynamic stiffness, the higher the structural sensitivity. Therefore, driving point dynamic stiffness is an important factor for controlling structural sensitivity transmission.

1.3.4.3 Acoustic Sensitivity

When a sound source is delivered to the body, some of the sound is reflected back, some is absorbed by the body, and some is transmitted to the interior through the body. Acoustic sensitivity is defined as the ratio of the interior sound pressure (P_{in}) to the outside source sound pressure (P_{out}) and is expressed as P_{in}/P_{out}. The acoustic sensitivity is the sound–sound transfer function, also known as sound–sound sensitivity.

The main sound sources outside the body include engine sound, exhaust tailpipe sound, air intake sound, and sound generated by friction between the tires and the road surface. These sources pass through the body and enter the interior. Figure 1.32 shows the transfer process of acoustic sensitivity. The acoustic sensitivity reflects the impact of the external sound sources on the vehicle interior noise, which depends on the sound insulation and sound absorption performance of the body.

1.3.4.4 Sensitivity Distribution Charts

Sensitivity is a function of frequency. If the sensitivities of different transfer paths are drawn on a sensitivity distribution chart, the noise and vibration contribution of each path at different frequencies can be clearly seen. There are two ways to present the sensitivity distribution.

The first way is to use curves, as shown in Figure 1.33. The abscissa is the frequency, and the vertical axis is the sensitivity value. Figure 1.33 shows the sound–vibration sensitivities of several structural-borne sound transfer paths. The response is the noise perceived by the driver, and the excitation points include the engine mountings, exhaust hangers, and so on.

The second way is to use a color map, as shown in Figure 1.34. The abscissa is the frequency, and each bar on the ordinate represents the sensitivity of one transfer path. The color represents the sound–vibration sensitivity value. In this figure, the excitation points include engine mountings in three directions, x, y, and z, and several exhaust hangers.

From the color map, it is easy to identify the contributions of each transfer path to the interior sound at different frequencies.

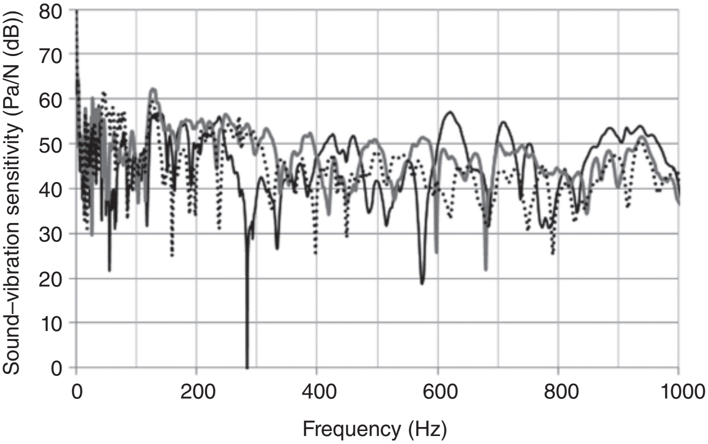


Figure 1.33 Sound–vibration sensitivity curves.

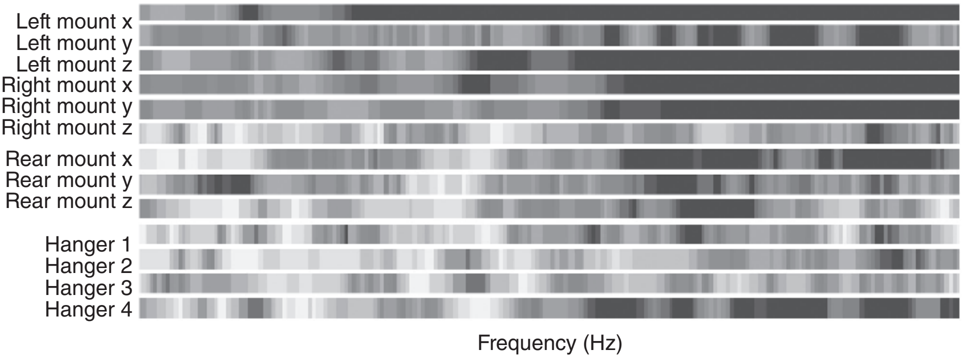


Figure 1.34 A color map of sound–vibration sensitivity.

1.3.5 Wind Noise and Control

The noise induced by the interaction between a moving vehicle and the airflow is called wind noise, also known as aerodynamic noise. When a vehicle is driven at high speed (such as $120\,\mathrm{km\,h^{-1}}$), the wind noise becomes prominent, and could even mask the engine noise and road noise. Customers are usually sensitive to wind noise, and if it is high, they may complain that it sounds as if a window or door is not completely closed, or that it affects their ability to hold a conversation or listen to the radio. Wind noise is dominated by middle- and high-frequency components. Today, people spend more and more time on highways, and their demands for low wind noise have become a prominent requirement for vehicle development.

The research areas of wind noise include:

- classification and mechanism of wind noise
- influence and control of body styling on wind noise
- dynamic sealing
- evaluation, testing, and analysis of wind noise.

1.3.5.1 Classification and Mechanism of Wind Noise

The interaction between the airflow and different body locations generate different noise sources that can be divided into four categories.

The first category is pulsating noise. The airflow acting on the body surface generates a vortex, as shown in Figure 1.35, which forms pressure fluctuations on the body surface. The noise generated by vortex disturbances is called pulsating noise. Beyond the vortex layer, the airflow is stable: this area is called the stable flow layer. In the vortex layer, the airflow creates a lot of small vortices attached to the body surface, which generate the pulsating noise. The noise generated by interactions between the airflow and body protrusions (such as the antenna) is also pulsating noise. Pulsating noise is formed outside the vehicle, but it passes through the body and enters the interior, so the noise transmission is airborne sound transmission.

The second category is aspiration noise. The wind noise outside the vehicle can pass through the body apertures and enter the interior. Even if there are no apertures on the body when it is standstill, small openings could appear between parts such as the doors

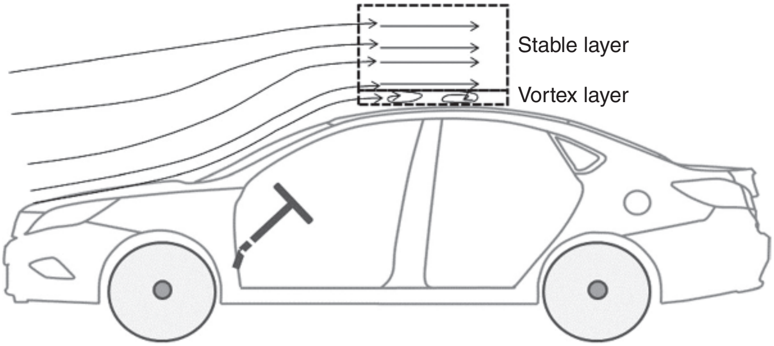


Figure 1.35 Airflow vortex layer and stable layer.

and the body frames when the vehicle moves. Wind noise that penetrates apertures or openings is called aspiration noise.

The third category is buffeting noise. When a sunroof or side window is opened, the body works like a resonator, and a low-frequency booming called buffeting noise will be generated by the interaction between the airflow and the opened body cavity.

The fourth category is cavity noise. Gaps always exist on the body surface, such as gap or margin between an A-pillar and a door. If the gap is large enough, a small cavity will be formed. When the airflow enters the small cavity, the airflow oscillates inside the cavity and generates cavity noise.

Pulsating noise and cavity noise pass through the body and enter the interior. Aspiration noise and buffeting noise directly enter the interior through body openings. If the openings are small, the wind noise is aspiration noise, whereas if the openings are large, the wind noise is buffeting noise. In short, all four categories of noise enter the interior by airborne sound transmission.

The vortices attached to the body surface excite the body panels like numerous small hammers. The excited panels radiate noise to the interior: this is structural-borne sound transmission of wind noise.

1.3.5.2 Influence of Body Styling on Wind Noise

Vehicle styling is one of the main influences on wind noise. The styling includes overall body styling and local structure styling.

In terms of overall body styling, the body should have a streamlined contour, and the transitions should be as smooth as possible. There are many transition surfaces on the body, such as the transition from the engine hood to the front windshield, and these surfaces must have sufficient curvatures and be smooth. Protrusions and large gaps on the body surfaces must be avoided. For example, protrusions underneath the vehicle, such as the exhaust system and subframe, can be hidden by a belly pan cover to achieve smooth surfaces, as shown in Figure 1.36. The small gaps reduce the possibility of generating cavity noise and pulsating noise.

Local structure styling and design involves many components, such as the side mirrors, antenna, door handles, and roof luggage rack. The local structure styling should follow

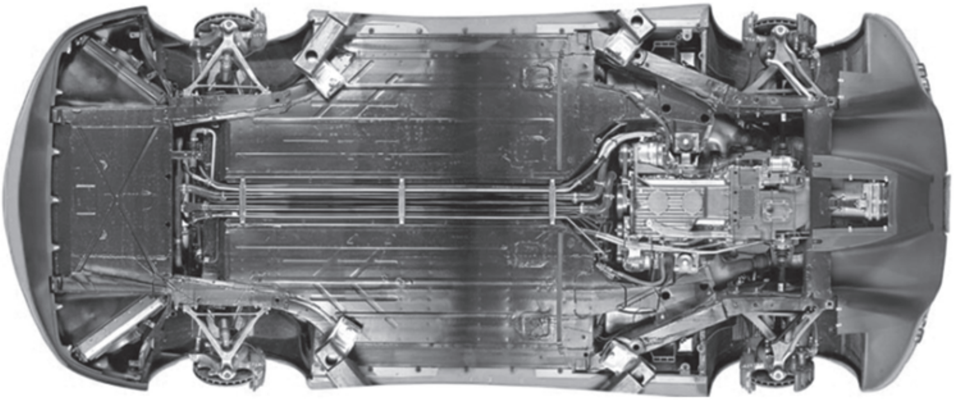


Figure 1.36 Underbody belly pan cover.

several principles. The first is to hide the local components beneath the airflow. For example, the door handle and door should be designed on the same plane. The second principle is that the local structures should have good streamlining so that air flows smoothly along the structures. The third principle is to guide the airflow away from sensitive areas: for example, a deflector can be installed at the front of the roof so that the airflow cannot directly move into the body cavity and buffeting noise is avoided. The fourth principle is to break the single-frequency pulsating noise: for example, a cylindrical antenna can cause an annoying tonal noise, but a spiral antenna can disperse the noise.

1.3.5.3 Control of Dynamic Sealing

The sealing described in the section "Sound Package for Vehicle Body" is static sealing. Static sealing involves sealing holes on the body when the vehicle is at a standstill, and its purpose is to prevent noise, dust, water, etc. from entering the vehicle. Dynamic sealing refers to the sealing between the relatively moving components for a moving vehicle. Gaps or openings between relatively moving components could appear when a vehicle moves even if the static sealing is prefect. A good sealing has the capability to dynamically compensate for gaps that form as a result of the components' movement.

If the body is not dynamically sealed, wind noise will directly pass through the dynamic gaps on the body and enter the interior, generating aspiration noise. Poor dynamic sealing usually generates noise problems at frequencies over 300 Hz.

The main factors affecting dynamic sealing are deformations of the body, doors, and other structures, and deformations of the seals or leakage caused by structural deformations that are not dynamically compensated for. The body and doors must have high enough stiffness and modes so that their structural deformations can be controlled. The deformations should be controlled within the elastic deformations of the seals.

In terms of seals, the main factors affecting dynamic sealing include the amount of elastic deflection and compression load. The design of a seal encompasses material selection, cross-section shape, load analysis, and so on. The variation of compression load with deflection should be as small as possible to meet the requirements of both the dynamic sealing and door closing force. The cross-section of a seal has a great influence on the compression load. There are two typical cross-sections: a single-bulb seal and a double-bulb seal. The curves of the compression load varying with the deflection are relatively flat for double-bulb seals.

1.3.5.4 Evaluation, Testing, and Analysis of Wind Noise

Evaluation and testing of wind noise can be implemented in a wind tunnel and proving ground. The indexes for evaluating wind noise are usually SPL, articulation index, and loudness, and so on. In the proving ground, interior noise can be subjectively evaluated and tested. In the wind tunnel, not only interior noise but also outside wind noise can be tested simultaneously. Beamforming (also called acoustic camera) or acoustic mirror can be used to measure the wind noise outside the vehicle, while a laser vibrometer can be used to measure body panel vibration.

In analysis of interior wind noise, the source–transfer path–receiver model in Figure 1.13 can be used. The source is the wind excitation exerted on the body: i.e. surface pressure fluctuation. The distribution of surface pressure can be measured in the wind tunnel via many small pressure sensors or microphones placed on the body surface.

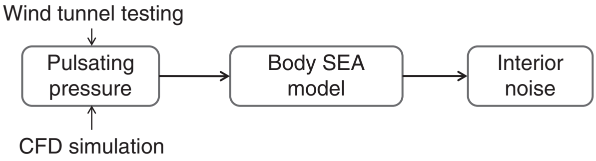


Figure 1.37 Source–transfer path–receiver model used in wind noise analysis.

The surface pressure can be also calculated using the computational fluid dynamics (CFD) method. The components of wind noise are in the middle- to high-frequency range, and a statistical energy analysis (SEA) is used to analyze the model, as shown in Figure 1.37.

1.3.6 Door Closing Sound Quality and Control

Many components on the body can be opened and closed, such as the doors, trunk lid, hood, glove box, and sunroof. When they are closed and opened, sound is generated, and excessive sound can have a negative effect on the customer's perception. Among these components, the doors are the most frequently opened and closed: therefore, the sound quality of a closing door is used as an example to illustrate the sound quality in this section.

The study of closing door sound quality includes subjective evaluation and objective evaluation, and methods for controlling the sound quality.

1.3.6.1 Door Closing Sound Quality

In fields such as ship and aircraft engineering, studies of noise and vibration do not include harshness: i.e. the subjective sensation on the human body. But harshness is given special attention on automotive engineering: this is because people have a much closer relationship with automotive vehicles than with aircrafts or ships. In modern society, the automotive vehicle is not only a transport tool, but also an entertainment "toy," so it has a significant impact on people's daily lives. Customers expect comfortable, delightful, and economic vehicles with good sound quality.

Noise and vibration mainly relates to frequency, but it can also relate to engine speed and firing order, which creates the unique characteristics of the vehicle's sound.

A quality is a feature that makes an object unique. Sound is the reception of audible mechanical waves and their perception by the brain: i.e. the human auditory impression. But sound quality is the combination of "sound" and "quality": that is, the unique sensations of the sound. Today, sound quality has become an important attribute of automotive NVH. The work of NVH engineers is not only to reduce noise and vibration, but also, and perhaps even more importantly, to enhance the sound quality. Sound quality has become an important part of automotive DNA.

Door closing sound quality refers to customers' perception of the sound generated at the moment of closing the door, and it can be an important component of a customer's decision to purchase a vehicle. When customers evaluate vehicles at stores or showrooms, they usually pull and push the doors. Along with the vehicle's overall styling, closing the door provides the customer's first impression of the vehicle. If they heard a low-level, single-impact, solid, and clean sound, they might think it is a good vehicle. But if they heard a loud, multi-impact, sharp, fragmented, metal-percussion sound, they might judge it as a bad vehicle, and even have doubts about the vehicle's quality and safety.

1.3.6.2 Evaluation of Door Closing Sound Quality

When customers close a vehicle door and hear a single-impact, clear, vigorous, solid sound, they will perceive it to have good sound quality. But if they hear a sharp, fragmented, multi-impact, "ring-down" sound, they will perceive the sound quality as poor.

Door closing sound quality involves both subjective evaluation and objective evaluation. Subjective evaluation is when a group of people subjectively score the door closing sound quality. Usually, a 10-point scoring system is used, and the higher the score, the better. Objective evaluation is when the sound data are recorded and processed, and

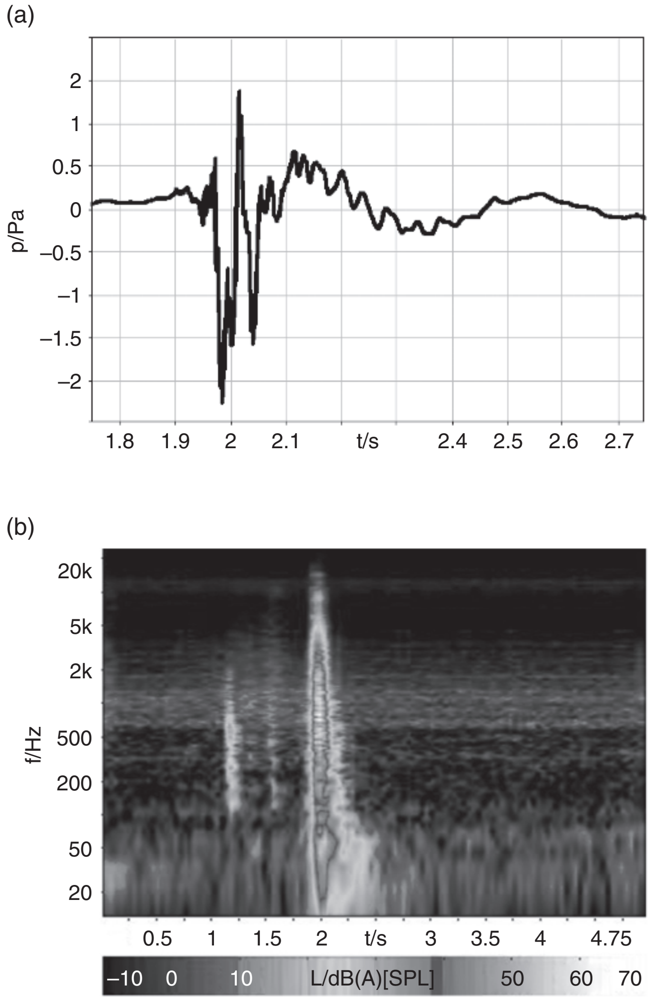


Figure 1.38 Curve and spectrum of a door closing sound. (a) Time-domain curve. (b) Time-frequency color spectrum.

some specific physical indexes are used to evaluate the sound quality. There are many indexes for describing sound quality, such as loudness, sharpness, articulation index, tonality, modulation (fluctuation and roughness), and order. Vehicle sound quality include the power train sound quality and electrical sound quality, and different indexes are used for evaluation of the different systems.

The indexes for objectively describing the door closing sound quality are loudness, sharpness, and ring-down. The time-frequency color spectrum should be analyzed together with the above indexes. Loudness is an auditory sensation index based on sound magnitude that is dominated by low-frequency components. Sharpness is a psychoacoustic index to measure the high-frequency components of a given sound. The sharpness can be interpreted as the ratio of the high-frequency components to the overall sound level. Ring-down refers to the lingering of a sound generated by the collision of two objects, and can be represented by a time-domain curve or a time-frequency color spectrum, as shown in Figure 1.38. From the curve or color spectrum, the frequency composition, number of impacts, and ring-down (or sound attenuation) of the door closing sound can be discerned.

1.3.6.3 Control of Door Closing Sound Quality

During the door closing process, the door and body are subjected to three impacts: the impact between the door and the body frame, the impact inside the door lock, and the impact of the seals during the process of being compressed. When the door is subjected the impact force, the door and accessories (such as glass, internal panels, etc.) generate sound that radiates to the air and can be heard inside and outside the vehicle, and the jiggle on the door panels and the shake of the trimmed parts and glass can be observed.

Door closing sound quality is affected by the stiffness of the door, the structure of the outer and inner panels, the lock structure, the structures of the latch and paw, the seals, the driving point dynamic stiffness of the striker, and so on. These factors must be analyzed to achieve a good door closing sound quality. The influence of the door, lock, and seal on the sound quality is briefly described below.

The outer panel and inner panel of the door must have sufficient stiffness, otherwise they will generate a number of “twitter” sounds. The stiffness of the outer panel can be increased by adding supporting beams and/or pasting reinforcement adhesives on its internal side. The stiffness of the inner panel can be enhanced by punching ribs on its surface. The locations at which door locks and speakers are installed must have sufficient local stiffness. Damping pasted on the panels can suppress their vibration and sound radiation.

The striker is mounted on the body and is subjected to impact from the latch, so the driving point dynamic stiffness of the striker must be sufficiently high. If the lock body is wrapped by soft materials (such as rubber, etc.), it will be well isolated and the radiation sound induced by the internal impact can be reduced.

The seals also have a significant impact on door closing sound quality. The seals prevent direct metal impact between the door and the body, and also reduce the sound generated by the impacts between the latch and striker and by the lock’s internal parts. The door closing force should be evenly distributed across the seals to enhance the sound quality and hand sensation of the door closing action. Therefore, the compression load distribution and the elastic deflection of the seals are important factors for controlling door closing sound quality.

1.3.7 Squeak and Rattle of Vehicle Body

S&R refers to the abnormal and irregular sounds generated when a vehicle moves, which can be random and inconsistent. S&R is different from engine noise, road noise, and wind noise, which tend to be regular and last for a relatively long time or exist all the time. Engine noise, for example, is consistent and directly relates to the firing order and resonance of the structures. The research scope of S&R includes:

- mechanism of S&R
- identification of S&R
- control of S&R.

1.3.7.1 Mechanism of S&R

In S&R, squeak refers to a transient noise generated by the friction between two objects, as shown in Figure 1.39a. All forms of friction, including friction between metals, between metal and rubber, and between rubbers, have the potential to generate squeak. Squeaks can occur in many locations of the body: for example, friction between a front door and A-pillar could generate a squeak.

Rattle is a transient noise induced by the impact between two objects, as shown in Figure 1.39b. Rattle can be generated by impacts between metal and rubber or between metals, such as the impact between the latch and striker of a groove box. In another example, the connection between the bolts and internal parts inside the instrument panel (IP) could become loose, so that when the vehicle is driven on rough roads, the internal parts impact one another and cause a rattle.

1.3.7.2 Identification of S&R

S&R can be identified by testing, and can also be predicted by CAE analysis.

Testing can be done on the road or on a four-poster simulator. Testing on the road involves subjectively and objectively evaluating S&R problems by driving a vehicle on different roads and at different speeds. Some S&R can be heard on all roads, but some can only perceived by certain roads; thus, S&R should be tested on all possible road surfaces, including asphalt, cement, corrugated roads, random shock roads, cobblestones, bricks, bumper roads, gravel, and so on. S&R also relates to the vehicle's speed: S&R problems can appear at some speeds, but disappear at others.

For road testing, S&R problems are usually identified by subjective scoring. The evaluators drive the vehicles and score the severities of S&R on different roads. The vehicle S&R scores and road conditions are considered simultaneously; a comprehensive index, the S&R index (SRI), is used to represent the vehicle's overall S&R severity. The SRI is the summation of the vehicle's S&R contributed by all parts and on all tested roads. The

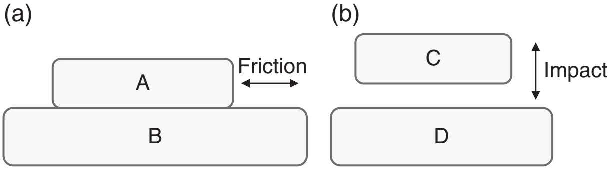


Figure 1.39 (a) Squeak. (b) Rattle.

lower the SRI, the fewer S&R problems there are. After the locations generating S&R have been identified, the S&R magnitudes can be determined by the tested accelerations and SPLs.

S&R problems are also commonly identified on a four-poster simulator. The simulator consists of four individual exciters, and the vehicle's four tires are placed on the corresponding exciters. Each exciter can generate a range of vibration signals, including random signals, sine sweeps, single-frequency inputs, and the collected road spectrum, and the four exciters can move in phase or out of phase. Compared with road testing, one advantage of simulator testing is that the evaluators can carefully identify S&R both inside and outside the vehicle, and can also identify the exact locations generating the S&R by using an NVH stethoscope.

S&R CAE analysis can be used to identify potential S&R-generating locations, and also to predict their probability. The S&R FE analysis includes: analysis of body stiffness and mode, modal analysis of the subsystem, body S&R sensitivity analysis, and overall vehicle response analysis. Insufficient body stiffness is the most important cause of S&R problems, so an analysis of body stiffness and the deflection of the door diagonal can be used to predict impacts between the door and body.

1.3.7.3 Control of S&R

The main causes of S&R problems include inappropriate gaps in body design, poor tolerance control, imprecise assembly or weak installation, poor compatibility of contacted materials, and low structure stiffness and mode.

S&R control involves not only testing the prototype vehicle to identify S&R problems, but also implementing S&R control across the whole vehicle development process. In the design phase, the clearance between adjacent components, the compatibility of materials, and the distribution of fasteners and bolts should be determined. Digital mock up (DMU) checking means identifying NVH and S&R problems in digital vehicle designs and using the data to check gaps between adjacent components, the connection status of wires and pipes with the body and interference between them, the material compatibility characteristics of parts in contact, the connection methods of the connected parts, the spans of the connected points, potential resonance, and so on. FE analysis is used to determine body stiffness, S&R sensitivities, and so on. In the prototype phase, the locations generating S&R are identified by road testing and four-poster simulator testing. In the mass production phase, the main work is to check the quality of parts, the quality control of the entire production process, and the performance of the produced vehicles.

1.4 Noise and Vibration Control During Vehicle Development

It usually takes around 3 years to develop a brand new vehicle, and NVH control takes place throughout the entire development cycle. At the beginning of development, the main work involves benchmark testing and analysis: i.e. analyzing the body NVH characteristics of competitor vehicles and setting up targets for the body's NVH. In the middle phase of development, the NVH work involves optimizing the body structure by CAE analysis, checking the digital prototype, testing the BIW, and analyzing and designing the sound package. During the late phase of the development, the NVH work involves testing the leakage of the BIW and trimmed body, the sound absorption and sound insulation performance, the body mode and sensitivity, and so on.

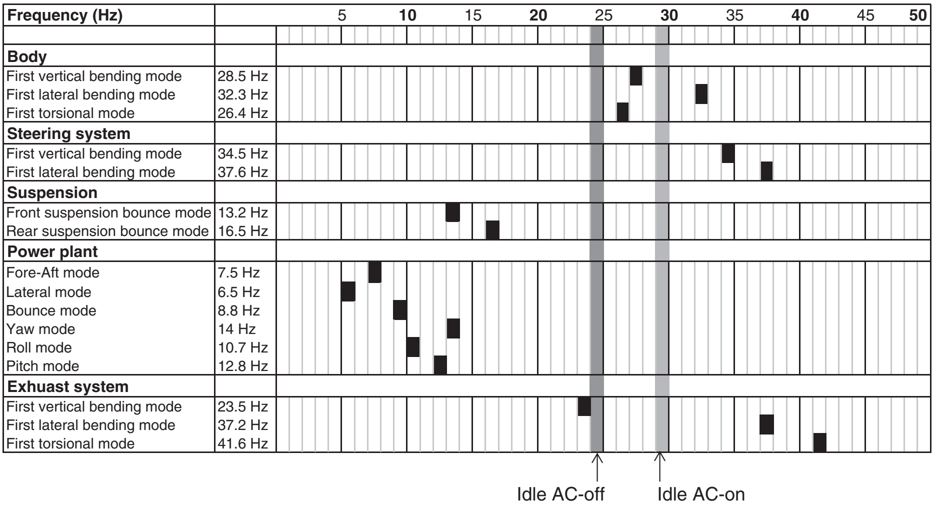
The NVH modal distribution and the NVH targets are used throughout the development process to guide NVH development. From target setting at the pre-development stage to target checking during the late phase, NVH work is deployed on the basis of the NVH targets, so developing suitable targets and effectively executing them is the key to ensuring good NVH performance of the developed vehicle.

1.4.1 Modal Frequency Distribution for Vehicle Body

The body carries all of the vehicle's systems and components, such as the engine, exhaust, and suspension. These interconnected systems have their own modes, and if their modal frequencies are the same or close, resonance could occur. Therefore, it is necessary to make a modal frequency table, listing the modal frequencies of all the relevant systems, so that it is clear where resonance could occur. In addition, after the frequency of each system has been determined, these systems can be developed independently. Vehicle development is a collaboration between an original equipment manufacturer and various suppliers, and many systems are developed in isolation.

During the early development phase, three modal frequency tables must be prepared: a vehicle modal frequency table, a body modal frequency table, and an excitation source frequency table. Figure 1.40 shows a vehicle modal frequency table.

The vehicle modal frequency table is the cornerstone of vehicle NVH development – it guides the development of the body and connected systems and components. The table includes the modal frequencies of the body and other main systems, along with the engine idling frequency, and it also shows the relationship between the modal



Frequency (Hz)	
Body	
First vertical bending mode	28.5 Hz
First lateral bending mode	32.3 Hz
First torsional mode	26.4 Hz
Steering system	
First vertical bending mode	34.5 Hz
First lateral bending mode	37.6 Hz
Suspension	
Front suspension bounce mode	13.2 Hz
Rear suspension bounce mode	16.5 Hz
Power plant	
Fore-Aft mode	7.5 Hz
Lateral mode	6.5 Hz
Bounce mode	8.8 Hz
Yaw mode	14 Hz
Roll mode	10.7 Hz
Pitch mode	12.8 Hz
Exhuast system	
First vertical bending mode	23.5 Hz
First lateral bending mode	37.2 Hz
First torsional mode	41.6 Hz

Figure 1.40 A vehicle modal frequency table.

frequencies of the connected systems: i.e. it provides information on the coupling between the body and the connected systems. The body modal frequency must be separated from the modal frequencies of the power plant, exhaust system, suspension system, and so on, as well as being separated from the engine idling frequency.

The body modal frequency table lists the frequencies of the overall body mode and local modes, and the main excitation frequencies. The main body local structures include the front panels, front floor, rear floor, front side frame, roof, steering wheel, mirror, and acoustic cavity, each of which has its own local mode. The local modes generate three kinds of noise and vibration problems: first, a local mode can resonate with the overall body mode; second, a local mode can resonate with a cavity mode; and third, a local mode can be excited by an outside source. The purpose of the body modal frequency table is to separate the local modal frequencies from the modal frequency of the whole vehicle, to avoid coupling between the local modes and the acoustic cavity mode, and to separate the local modal frequencies from the excitation frequencies.

The excitation source frequency table shows the frequencies of all possible sources of body excitation on a table or graph. These include stable excitation frequencies, such as the firing frequency during engine idling, as well as unstable excitation frequencies, such as frequencies during acceleration. There are many excitation sources, such as the engine, transmission, fan, tires, and so on. The purpose of making this table/graph is to compare it with the body modal frequency table to find frequencies at which the body may vibrate, and also to find methods to avoid such vibration.

Chapter 2 describes the body mode frequency table and excitation frequency table in detail.

1.4.2 Body NVH Target System

The body modal frequency distribution is a part of the body NVH target system. The body NVH target system consists of four levels: vehicle-level body NVH targets, trimmed body NVH targets, BIW NVH targets, and component NVH targets.

Vehicle-level body targets influence the whole vehicle's NVH performance, and include the body vibration targets and noise targets. The vibration targets specify bending and torsional modal frequencies for the body structure, and modal frequencies for panel structures (such as the dash panel, etc.) and accessories (such as side mirrors, instrument panels, etc.). The noise targets specify acceptable levels of vehicle air leakage and sound insulation, a range for the acoustic cavity mode, and parameters for door closing sound quality.

The vibration targets for the trimmed body include its bending and torsional modal frequencies, and vibration–vibration sensitivity of external vibration to interior vibration. External vibration refers to excitation applied to the body, such as the excitation applied by the power plant to mounting points on the body. Interior vibration refers to the perceived vibration of the steering wheel, seats, and floor. The noise targets for the trimmed body include the sound–sound sensitivity of external sound excitation transmitted as interior sound, and the sound–vibration sensitivity of external excitation transmitted as interior sound. External sound excitation includes engine radiation noise, exhaust orifice noise, and so on, and interior sound refers to sound heard by the occupants.

The BIW NVH targets include its bending and torsional modal frequencies, the modal frequencies of the panel structures, and the driving point dynamic stiffness. All of the function and manufacturing process holes on the BIW are blocked up in order to check its air leakage; the air leakage of the BIW is set as a noise control target.

The component targets refer to accessories connected to the body and include the modal frequencies of brackets, the engine hood, trunk lid, and so on; the sound absorption coefficient and sound insulation coefficient of the sound package; noise reduction; and targets relating to the door, such as the modal frequencies of the internal and outer door panels, and the driving point dynamic stiffness of the striker.

1.4.3 Execution of Body NVH Targets

The body modal frequency table and the NVH target system provide the guidelines for body NVH development. Strict implementation methods and procedures are necessary to achieve the NVH targets. The vehicle development process is divided into many milestones, and a target implementation plan and execution results should be clear for each milestone. The first goal is to achieve the component targets and BIW targets, then to achieve the trimmed body targets, and finally is to achieve the overall vehicle targets.

In the implementation process, milestone checking is very important. The vehicle program's chief engineer and the NVH chief engineer organize a special meeting to check the input goals and output requirements for each milestone. If the milestone requirements are not met, a risk analysis must be conducted and the work for the next milestone needs to be determined.

1.5 Structure of This Book

This book comprehensively expounds the mechanism and control methods of vehicle body noise and vibration. This book is divided into nine chapters, and covers the overall body vibration and mode, local structure vibration and noise, the sound package, sensitivity, wind noise, sound quality, S&R, and the NVH target system. The contents of each chapter are briefly described below.

Chapter 1, "Introduction" introduces the body structure and the noise and vibration problems induced by the body. It describes structural-borne sound and airborne sound, and their transfer paths to the vehicle interior. Based on analysis of the transfer paths, the key technologies of NVH control, such as body structure vibration control, the sound package, wind noise control, and sound quality control, are explained concisely. Body NVH control during vehicle development is briefly introduced, including establishment of the modal frequency tables and target system, and milestone checking.

Chapter 2, "Vibration Control of Overall Body Structure," describes NVH problems relating to the overall body structure. The overall body stiffness and mode are the cornerstones of vehicle NVH. The overall body stiffness is determined by the overall layout of the body structure, frame stiffness, joint stiffness, adhesive stiffness, and so on. This chapter describes the testing and analysis of body stiffness and modes. The principles of decoupling between a system and an excitation and decoupling between adjacent systems are illustrated.

Chapter 3, “Noise and Vibration Control for Local Body Structures,” describes mechanisms of and control methods for body panel vibration and sound radiation. The stiffness and mode of the overall body frame structure affect the whole vehicle’s NVH performance and S&R, while the modes of the local panel structures create noise problems at specific frequencies. The body panels include the dash panel, floor, roof, trunk lid, and so on. This chapter introduces coupling between the panel structural modes and the acoustic cavity mode, mechanisms of panel vibration and sound radiation, and the potential interior booming induced by the panels. This chapter also describes methods for changing panel stiffness and suppressing vibration, such as stiffness control, damping treatment, and so on. Finally, the chapter describes NVH control of several key components, such as brackets, the steering system, and the seats.

Chapter 4, “Sound Package,” describes the mechanisms of sound absorption and sound insulation materials and structures. Static sealing is the most basic technology for the sound package. This chapter describes the measurement of and control methods for body sealing and cavity baffling. Sound absorptive materials and structures provide the main method for eliminating high-frequency noise, whereas sound insulation materials and structures provide the main means of eliminating low- and middle-frequency noise. This chapter describes in detail the application of sound absorption and sound insulation to the body.

Chapter 5, “Vehicle Body Sensitivity Analysis and Control,” explains body NVH sensitivity from the perspective of the source–transfer path–receiver model. This chapter describes the characteristics of noise and vibration sources that are applied to the body, which are closely related to the body’s sensitivities. Structural sensitivity represents the transmission of body structural vibration as interior noise and vibration, whereas sound sensitivity describes the transmission of exterior sound sources to the interior. This chapter also introduces driving point dynamic stiffness, which is closely related to structural sensitivity, and methods for controlling it.

Chapter 6, “Wind Noise,” describes mechanisms of and control methods for wind noise when the vehicle is driven at high speed. This book classifies wind noise as pulsating noise, aspiration noise, buffeting noise, and cavity noise, and this chapter describes the mechanism of each in detail. In this chapter, the problems of wind noise caused by improper overall styling and local design are expounded, and the methods for controlling wind noise from a design perspective are given. Whereas static sealing is the basis of the sound package, dynamic sealing is the cornerstone of body wind noise control; this chapter describes the mechanisms and control methods for dynamic sealing, along with methods of wind noise testing in wind tunnels and on the road, and the numerical calculation method for wind noise.

Chapter 7, “Door Closing Sound Quality,” introduces the concept of sound quality and evaluation indexes, and three kinds of sound quality problems including power train sound quality, electrical sound quality, and door closing sound quality. This chapter describes in detail the characteristics of door closing sound quality, the relationship between the sound quality color map and door components, and control methods for improving door closing sound quality.

Chapter 8, “Squeak and Rattle Control in Vehicle Body,” describes the S&R phenomenon. The mechanisms of S&R are very complex, involving a lot of nonlinear problems. The locations and severity of S&R can be identified by testing on the road and/or by using a simulator. This chapter also emphasizes that S&R control can begin during the pre-development phase through body stiffness and modal analysis, subsystem modal analysis, body sensitivity analysis, and vehicle response analysis. Finally, this chapter details S&R control across the entire vehicle development process, including structural integration design, DMU inspection, matching of material friction pairs, and manufacturing process control.

Chapter 9, "Targets for Body Noise and Vibration," describes the principles of body NVH target setting, cascading, and control. Starting with the body structure, the chapter introduces NVH targets for the vehicle-level body, trimmed body, BIW, and components.

A few topics repeatedly appear in different chapters because they are associated with each other, which should help readers to deeply understand some particular interrelated problems.