Transmission loss of vehicle seals

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The thesis consists of an introduction and the following two papers:

Paper A
Measurement of Sound Transmission Loss of Vehicle Seals.
To be submitted.
Part of the paper has been presented in Inter-Noise 2008, Shanghai, China.

Paper B
Prediction of Sound Transmission Loss of Vehicle Seals.
To be submitted
Part of the paper has been presented in Inter-Noise 2008, Shanghai, China.
1 Introduction

When a vehicle is cruising at a speed over 120kph, the wind noise will play the dominant role for the interior noise \[1\]. Measurements show that the wind noise level at the passenger ear is reduced by 1-3dB by changing from a single-seal to a double-seal, and is further reduced by 1-3dB when a lead tap is added \[2\]. It indicates that the noise through the vehicle seals is a major contributor to the wind noise. Consequently, improvement of the sound transmission loss through the vehicle seals is an essential method to reduce interior wind noise level.

Vehicle door seals, located around the passenger door as seen in Figure 1\[3\], play a major role in determining isolation of the passenger compartment from water and reducing wind noise inside the vehicle. Figure 2 shows a typical vehicle door sealing system. The seals minimize the wind noise inside the vehicle by two methods: first, the seals must remain in contact between the door and the car body to close all direct noise paths from the vehicle exterior; and secondly, the seals must attenuate the noise from the door edge and vehicle exterior to the greatest possible extent. Aspiration noise is produced when the seal is imperfectly designed which will significantly promote the interior noise \[4\]. In the recent years, great efforts have been put on the door closing effects \[5, 6\]; while acoustic mechanism of the vehicle seals is often neglected because of the complex geometry of the cross section.

![Figure 1 Location of door seals](image1)

![Figure 2 Cross section of door sealing system](image2)

Bulb seals are commonly used where the seals must accommodate the variations of the structure in door gap closure. Most of the door seals are made from foamed rubber so that they can readily be adapted to different mating surfaces and car frames. There are three possible mechanisms for aerodynamic noise being transmitted to the interior of a car \[7\]:

1. Sound transmission through the seals themselves;
2. Sound transmission through the vibration of the structural components supporting the seals;
3. Leakage through imperfectly sealed locations where a small gap exists.

The first mechanism is studied in this thesis. Reverberation room test is prevailing in the literature, where a line specimen of the vehicle seal and the simulative assembly parts are used to obtain sound insulation characteristics of the vehicle door seals. It is also proposed, by using the reciprocal principle, to use a reverberant box to measure sound insertion loss of line specimen of seals. Reverberant sound field is created inside the box and the intensity is measured outside of the box (Figure 2). In this case the intensity of incident sound is obtained by measuring the intensity of sound output when no test piece is fitted. Won Wook Jung proposed to build a box with a similar shape compared with the vehicle cabin. Sound is created outside the box and a sound probe is measuring inside the box, as seen in Figure 4.

There are also acoustic measurements on running vehicles. The influence of different gaps of sealing system is investigated by Peng. Sound pressure levels around the vehicle door are recorded. Karim Haddad uses acoustical imaging technology to localize the acoustic sources inside a vehicle. However, considering the complicated vehicle body and multiple inner sound sources, it is not a good idea to perform such a test to find the acoustical mechanism of a sealing system at the prototype stage.

Rubber is a non-linear material. The nonlinear behavior increases the complicity of the problem. However, the change of material properties with temperature and time is not of the interest of the current study. For a given condition, the static load does not change when the door is closed. The dynamic load due to the incident sound pressure, on the other hand, is not that high and can be considered as linear. As a result, for the current study, the mechanism of the sound transmission through the seal can still be assumed to be a linear process.

For the prediction of the sound transmission loss of a vehicle seal, it is proposed in [2] to simplify the complex structure of the seal into multiple partitions, with the distance between two membranes determined by the size of the cavity (double-membrane model),
as illustrated in Figure 5. This model is investigated in this thesis. Possible improvements as well as problems are discussed.

Fig. 5 Double membrane model

The prediction of the transmission loss by using finite element method is also a common practice \cite{3,10}. The procedure consists of two steps: static analysis and acoustic analysis. FEM method can be used to find suitable designs to satisfy both requirements: door closure force and sound transmission loss. This approach is also included in this work. The results of the FEM model are then compared with the improved double-membrane model to see the advantages and disadvantages of the models and the applicable frequency ranges.

2 Summary of the results

Reverberation room test and semi-anechoic chamber test are performed for the acoustic properties of the seal. For the measurements of the sound transmission loss, the test seal-strip is mounted in a specially designed frame in between a reverberation room and an anechoic tunnel. The reverberation room is used as the source room and the transmitted sound is measured inside the anechoic tunnel. Three methods are used for the transmitted sound: sound pressure level at the middle of the tunnel, sound intensity level at the middle of the tunnel and the average sound intensity level. Results show that the sound pressure level test can reach the same result if the measurement is performed in the anechoic tunnel.

The insertion loss of seals in a practical car is tested in the semi-anechoic room. Two loudspeaker-arrays are used at the both sides of the test vehicle, in order to produce a uniform plane sound wave incident to the doors of the vehicle. Results show that the sound pressure levels of the interested area are quite uniform with the bias of the A-weighted sound pressure level no more than 1dBA when the chamber is empty. However, the sound pressure levels differ some in the passenger door area due to the complex shape of the trial vehicle body when the test vehicle is placed in the center of the chamber. The comparison of vehicle interior noise shows that sound pressure level at passenger's ear position is similar to those in the door area, indicating that the sound power is mainly transmitted through the door seals area into the vehicle.

Results of the measurements prove the feasibility of this semi-anechoic room method. The simulation of the vehicle seals installations reveals different compression shapes of the vehicle seals created in the reverberant room tests, which may have a big contribution to the deviation of the experimental results.
A vehicle seal is usually made of a foam rubber, which shows a nonlinear behavior. Strain energy function is often used to simulate the mechanical properties of the seal \cite{11}. However, since the level of the incident sound pressure is not that high, a linear model may still be used for the problem of sound transmission when other conditions are fixed. The ANSYS \cite{12} finite element code can be used to perform the nonlinear analysis of the large deformations of the seals. Other nonlinear finite element codes such as MARC, ADINA or ABAQUS could also be used to analyze the seal system. \cite{13} The seal to metal contact stress distribution is obtained from the analyses at various stages during the compression. The contact analysis reveals that the inner stress intensity increases quickly during the installation. Nevertheless, the properties of the sound transmission losses do not show any apparent relationship with the increased stress. This fact implies that the increased stiffness during the compression procedure also does not influence its acoustic properties much.

By using of double-membrane model, the complex seal cross section is simplified into multiple partitions. The distance between two membranes is determined by the space inside the seal. Double-wall resonance is an important feature of such a structure. Below the double-wall resonance, the wall works as a single leaf. After that, the effect of double wall appears. Comparison with measurements shows that the simple double-wall model does not work at high frequencies. Some modification must be included. Also, the resonance frequency predicted by this simple model is about less than half of the measurements, as seen in Fig.6.

Several reasons for the big discrepancy are discussed. Firstly, the influence of the sound transmission through the side material (path A and C in Figure 5): those two paths do not show double wall behavior and hence the sound transmission loss at high frequency should be lower. Secondly, the incident angle: The measurements are performed in the reverberation room; the incident sound wave is from all possible angles. In order to perform the second improvement, the influence of the thickness of the rubber material is also taken into account and the model of the sound propagation is as shown in Figure 7.
The prediction when all those factors are taken into account is shown in Figure 8. The high frequency behavior looks much better, although still higher than the measurements. This may be due to the over-simplification, since at high frequencies the exact shape of the seal becomes more important and the simplification shown in Figure 5 is not satisfactory anymore.

Finite element model, with the fixed boundary condition, is developed for the prediction of the relatively high frequencies. Results are shown in Figure 9. Indeed, the agreement is much better at high frequencies when the exact shape (before compression) is used. At low frequencies, however, the discrepancy is extremely large. This is because of the boundary condition: For a fixed boundary condition, the sound transmission loss tends to be infinite when the frequency is close to zero. For a vehicle seal, which is made of foam rubber, it is always possible to have some relative movement with the frame and the fixed
boundary condition is far away from the reality. Due to the compressibility of the form rubber, the exact boundary condition is difficult to define in linear assumption.

It is interesting to compare the basis of the simplified model with that of the FEM model used here: For the simplified model we didn't take into account of the bending stiffness of the rubber sheet, while for the FEM model the bending stiffness is included. It is this property which makes the large difference of the low frequency behavior. By comparing the predictions with measurements, it seems that for a linear model, neglecting the bending stiffness of the seal wall is a good choice to solve the problem of the boundary condition.

The problem of the big difference between the measured dip of the sound transmission loss with the predicted dip by the simplified model can be solved by using the cylindrical shell theory. A vehicle seal is actually more like a distorted cylindrical shell than a double wall. The dip in the transmission loss curve is due to the ring frequency of the corresponding cylindrical shell, not due to the double-wall resonance. By using the shell theory, the dip in the transmission loss curve can be correctly predicted.

An ideal cylindrical shell theory has also the problem at low frequencies due to the big bending stiffness. The sound transmission loss of a distorted circular duct, as shown in Figure 10 (from [14]), is much reduced due to the so-called mode coupling. To model a vehicle seal as a distorted circular duct may be a good choice and could be a continuation of the current work.
3 Conclusions and future work

In this thesis, reverberation room test and semi-anechoic chamber test are respectively studied. By comparing the sound pressure level, sound intensity level and average sound intensity level at the receiving side, it proves that a simple sound pressure level test may obtain same measurement accuracy when there is little reflected sound. Due to the complex shape of the trial vehicle, sound pressure levels differ in the passenger door area when laboratory tests were performed. The comparison of interior noise in the semi-anechoic room test shows that the sound energy is mainly transmitted through the door seals area into the vehicle. Comparison of sound transmission loss of two vehicles of the same type and sound pressure levels at passenger’s ear of three different vehicles also proves the feasibility of this semi-anechoic chamber test method. The simulation of the vehicle seals installations reveals different compression shapes of the vehicle seals created in the reverberant room tests, which may have a big contribution to the deviation of the experimental results.

The contact analysis shows the inner stress intensity increases rapidly during the installation procedure. Prediction methods of vehicle seals are discussed, which reveals the problem existing in the simplified model method. Some factors such as sound transmitting through the side material, thickness of material and integration of incident angle are taken into account. In the line specimen measurements, the source side is in a reverberation room, the incident sound is from all possible angles, whereas in the real case the angle influence is not that big since the seal is mounted in a “slot” and normal incidence is more important. This fact partly explains the reason why the insertion loss measured in the semi-anechoic room, which is close to a real situation, is much higher than the transmission loss measured in between a reverberation room and an anechoic tunnel.

Due to the properties of non-ideal shape of the seal (distorted shell), and due to the complicated boundary condition for real case, exact boundary conditions are difficult to
be defined. Results show that a simple double-membrane theory without taking into account of the bending stiffness of the rubber sheet is a good approach for the prediction of the sound transmission loss at low frequencies. At relatively high frequencies when the influence of the boundary condition is not that important, a FEM model with the exact shape and with the stiffness of the rubber sheet will yield better results. The ring frequency of a corresponding cylindrical shell explains the dip in the measured sound transmission loss.

For the better modeling of vehicle seals, more work is still needed to fully understand the acoustic mechanism. Meanwhile, seals with different cross section geometry should also be compared to enrich the experimental results.

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