Aural Discomfort Evaluation of Barometric Pressure in High-speed Train

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ABSTRACT

Interior pressure of high-speed train varies when it passes through tunnels, which usually caused different levels of aural discomfort. As tympanic membrane (TM) plays a prominent role in pressure energy conversion and transmission, a finite element (FE) model including annular ligament (AL), pars flacida (PF) and pars tensa (PT), was established in line with its anatomical structure. To quantitatively assess the barometric quality of train cabins, on-board tests were conducted to collect the interior pressure change history. Additionally, TM simulation in LS-DYNA was implemented to investigate the relationship between pressure changes and vibration characteristics. Based on the simulation results, displacement and velocity transfer function (VTF) of umbo were integrated as two indicators to judge aural discomfort and four discomfort levels were divided ranging from ideal, good, bad to worse. The results indicate that the threshold of displacement for each discomfort levels is $1.81\mu m$, $2.10\mu m$, $5.95\mu m$ and $11\mu m$.
respectively and the lower and upper bounds of VTF were confirmed as well. By imposing the recorded interior pressure onto TM surface, the displacement and VTF were produced. Depending on the established aural discomfort judgment method, the results derived from simulation under interior pressure load reveal that travellers in passenger cabin of head car experience large proportion of inner ear annoyance while crew in driver cabin undergo mixed discomfort from both TM and inner ear.

**Key word:** high-speed train, tunnel, inferior pressure, tympanic membrane, ear discomfort

1. **INTRODUCTION**

Aerodynamic topics related to high-speed train such as resistance and radiation noise have scarcely escaped researchers’ attention, but concerns about aural discomfort induced by transient interior pressure of the high-speed trains when travelling through tunnels or meeting in tunnels has been limited until recently. When train passes through tunnels at a speed of 300km/h, the pressure differential outside varies from -1kPa to 1kPa\(^1\). The transient pressure flows into the train by path of openings of the train and in turn brings different degrees of aural annoyance of passengers. This kind of barometric complaints of ears is frequently reported in blast, diving and aviation\(^2\)\(^-\)\(^4\), which accompany with TM rupture, bleed, perforation or hearing loss. However, aural complaints caused by tunnel-train coupling effect are less severe and controllable by means of improving air tightness of train. In 1999, Japan conducted series of experiments on revealing the relationship between human ears tinnitus and pressure changes\(^5\). TM is the first receptor of pressure wave and plays a critical role in energy conversion and transmission. Meanwhile, it is also the most sensitive and susceptible organ to pressure changes. Thus, an FE TM model was constructed to simulate its dynamics and to assess aural discomfort from perspective of ear biomechanics. Similarly, the FE TM model was also validated by frequency response analysis method.

Despite of subjective complaints of aural discomfort from travelers, the recorded interior pressure is not desirable to judge ear discomfort levels quantitatively. Furthermore, to assess quality of interior pressure, proper features should be used to correlate mobility of TM with ear discomfort. Displacement, volume displacement\(^6\), displacement transfer function (DTF)\(^7\)\(^-\)\(^8\), velocity\(^9\), velocity transfer function (VTF)\(^10\) are universally employed to explain the
dynamics of TM. Displacement and velocity are easy to yield in LS-DYNA, of which displacement is a convincing indicator to weigh the ear discomfort level. As time-dependent interior pressure can be achieved by tests, VTF of umbo is easy to be calculated. Consequently, displacement and VTF are used as two norms to assess the discomfort levels.

Our purpose is to assess the aural discomfort levels induced by interior pressure changes from perspective of biomechanics as train passes through tunnels.

2. MATERIALS AND METHODS

2.1 On-board Tests

On-board tests were conducted to collect interior pressure changes in different cars, here only head car (the first to run into tunnel) was selected for assessment. Two sensors were assembled in head car, which were fixed in driver cabin and passenger cabin respectively. At the instant time the train runs into the tunnel, the sensors were triggered to record the pressure changing history. The total tunnel length is 12.37km which costs about 125 seconds to travel at a speed of 350km/h. In the paper, the first 25 seconds were picked to investigate how positive pressure in the ear canal affects human ears’ discomfort.

2.2 FE TM Model

TM is anatomically segmented into three parts which respectively are AL, pars PF and PT. AL lies at the periphery of TM and separates PF and PT at antero-superior position. Moreover, the area of PT is much larger than that of PF. In addition, TM is conical in shape with a depth ranging from 1mm to 2mm. Thus, a TM model was constructed in line with its anatomical structure as shown in Fig.1.
The model has 2115 nodes and 2056 elements and cone node connection type was adopted between components. As TM is firmly attached to the sulcus of middle ear cavity, the edge of TM is set as fixed constraint. Besides, umbo of TM (node number 1609) was confirmed as the referential node to investigate its vibration characteristics.

The detailed material properties are shown in Table I.

| Component | Property   | Young’s Modulus E/MPa | Poisson Ratio ν | Thickness mm |
|-----------|------------|------------------------|----------------|--------------|
| AL        | isotropic  | 1.08                   | 0.3            | 0.12         |
| PF        | isotropic  | 11.19                  | 0.34           | 0.127        |
| PT        | orthotropic| $E_x$: 23.72           | 0.3            | 0.069        |
|           |            | $E_y$: 15.29           |                |              |
|           |            | $E_z$: 50.18           |                |              |

2.3 TM Simulation Settings

The key procedure in estimating the aural discomfort is to transform experiments done by Japan [5] into TM vibration characteristics. It is noteworthy that the experimental findings ranked the aural discomfort as four levels which are ideal, good, bad and worse respectively. Ideal level means human ears have no disturbing feeling to ambient pressure changes and worse level denotes the most hostile atmospheric environment for human ears. Based on the simulation results in LS-DYNA, it reveals the relationship between aural discomfort level and vibration of TM. Due to the minimum element size is 0.1mm, a step size of 1e-7s was assured for steady computation and accuracy. Besides, the pressure loads, which were implemented at the exterior surface of TM, include two sources: one is
identical to the experimental conditions and the other is from on-board tests. Except for these settings, Rayleigh damping ratio was also introduced, that is, alpha is set as 0 and beta 7.5e-5.

3. RESULTS

3.1 Interior Pressure History of Head Car

Fig. 2 displays the interior pressure changing history throughout the train’s passage. When the train runs into the tunnel, the air inside is compressed and propagates forward at sonic speed, which makes the interior pressure positive. With the continuous penetration in the tunnel, the interior pressure descends slowly until 23s after which the pressure drops sharply to about -0.7kPa. It also demonstrates that the pressure fluctuation histories in both cabins keep consistent tendency.

3.2 Aural Discomfort Judgment Method

Fig. 3 and Fig. 4 illustrate aural discomfort judgment method based on displacement and VTF of umbo. From Fig. 3 and Fig. 4, it reveals that the vibration of TM turns intensive with the lifting of discomfort level and each level corresponds with its certain threshold or bounds. If the displacement of umbo or VTF exceeds ceiling value or bounds, it is classified into the next discomfort level. The displacement thresholds for all levels are 1.81μm, 2.10μm, 5.95μm and 11μm.
respectively and the lower and upper bounds of VTF are also specified in Fig.4.

![Figure 3. Displacement criterion for aural discomfort assessment.](image)

![Figure 4. VTF criterion for aural discomfort assessment.](image)

It deserves notes that displacement criterion is integrated with VTF to evaluate the aural discomfort level in the following sections. Displacement is employed to assess the TM discomfort while VTF, which is related with the variations of lymphatic flowing state, can be used to estimate feelings of inner ear.

### 3.3 TM Vibration Characteristics under Interior Pressure

Fig.5 and Fig.6 exhibit the vibration characteristics of umbo under interior pressure loads. Here it should be pointed out that there are three referential dashed lines in Fig.5, which respectively are ideal level line, good level line and bad level line from bottom to top. Similarly, the three couples of referential lines in Fig.6 denote good, bad and worse levels respectively from inner to outer.
Figure 5. Displacement of umbo under interior pressure load.

Figure 6. VTF of umbo under interior pressure load.

From Fig.5, it indicates that the displacement of umbo is lower in passenger cabin than that in driver cabin and is mostly below the good discomfort level line. However, this doesn’t imply travellers in passenger cabin of head car experience no aural discomfort, because Fig.6 demonstrates VTF goes beyond the bounds of good level but within bounds of bad level most of the time history. Whereas in the driver cabin, the displacement curve goes under the good level line initially and then ascends to bad level line. Moreover, the displacement of umbo in driver cabin fluctuates more intensively than that in passenger cabin. And with respect to VTF, the curve in driver cabin changes with the bounds of worse level.

4. DISCUSSION

When the train runs into the tunnels, the compression wave inside the tunnel forces the interior cabin pressure increasing. But the interior pressure declines with the train’s running forward as shown in Fig.2. On the other hand, assessment of interior barometric quality is accomplished by virtue of findings on blast and aviation, because literatures on aural discomfort induced by tunnel-train coupling effect are quite limited from perspective of biomechanics. Pressure wave
generated by blast is more than ten times larger than interior pressure changes of high-speed train [2]. Blast injury of ears universally manifests in TM rupture, penetration, bleed or ossicle dislocation, while interior pressure may not cause these symptoms. Furthermore, altitude exposure during aviation also reported different degrees of ear complaints such as tinnitus or temporal hearing loss. Interior pressure fluctuation is much similar to the ascending and descending maneuvers of aircrafts [11]. Thus, our assessment of aural discomfort level in high-speed train borrows some of the achievements in aviation.

Despite the displacement of umbo doesn’t surpass good level line in the passenger cabin as is illustrated in Fig.5, it simply implies the interior pressure change makes insignificant difference on TM. The VTF curve in Fig.6 indicates that TM vibration energy transfers to inner ear through ossicular bones, which may bring otagia or tinnitus. Nevertheless, the displacement of umbo begins to exceed the good level line in driver cabin after 5s as is displayed in Fig.5, which makes the TM experience discomfort feelings such as ear fullness and earache. The explanation for these symptoms is that the positive pressure in the ear canal pushes the TM to deform interiorly. In the meantime, the VTF curve reveals that inner ear also appears discomfort. In Fig.6, the VTF curve goes beyond the bounds of good level lines constantly. TM vibration energy is transmitted to inner ear which converts the mechanical energy into electric energy and in turn causes inner ear annoyance. Here notifications should be pointed out that the pressure regulation function of Eustachian Tube (ET) is not considered as a result that ET generally works as a one-way valve. The precondition for it to be opened passively is when the pressure differential between middle ear and ear canal is 15mmHg (2kPa) positive [12]. However, the pressure differential recorded by on-board tests is negative, which represents the ET is triggered to work during the high-speed train’s passage. By comparison, it indicates that drivers experience mixed aural discomfort originated from both TM and inner ear, while aural discomfort is dominated by inner ear for travellers in the passenger cabin. In conclusion, the barometric environment in the driver cabin is more hostile than in the passenger cabin of head car.

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