Relationship between Train Speed and Aural Discomfort in Tunnels Based on Tympanic Membrane Model

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Abstract

Inferior pressure changes of high-speed train have been disturbing aural feelings of passengers and staff when trains are passing through tunnels or meeting in tunnels. However, it is problematic to quantify the extent of aural discomfort according to the recorded inferior pressure data. The paper presents an original methodology to assess humans' aural discomfort based on the mechanics of a reconstructed tympanic membrane(TM) finite element model. Besides, viscoelastic coefficients of a 7-parameter Maxwell model were obtained by inverse problem-solving method. By comparison with the results derived from the dynamic simulation of TM under varying pressure amplitudes and gradients, aural discomfort was ranked into four levels from ideal, good, bad to worse. Meanwhile, displacement, velocity and stress of TM umbo were chosen as referential indicators to establish judgement rules for discomfort assessment. In addition, the pressure change history which was exerted at the lateral side of TM, was collected by field tests when trains are running in tunnels. The results reveal that the maximum displacement of umbo for the four discomfort levels are 35.35μm, 44.22μm, 63.84μm and 99.07μm respectively. Furthermore, a set of methodology was established for judgement of aural discomfort. Also, it indicates that aural discomfort begins at the pressure inversion point before which human ears feel pleasant whereas exacerbates when trains running in the middle of tunnels and alleviates when approaching the tunnel exit.

1. INTRODUCTION

Train-tunnel aerodynamic problems have long been bothersome experiences for staff and passengers. For instance, the barometric pressure outside the train fluctuates from 1kPa positive to 1kPa negative when train is passing through tunnel at 300km/h [1]. The varying pressure travels interiorly by path of openings of compartments and may incur different extents of aural discomfort which worsens with increasing running speed and long tunnel conditions. Countries like French, Germany and Japan has enacted air-tightness standards for high-speed trains from either the pressure amplitudes or pressure changing rates. Nonetheless, it poses a challenge for researchers to evaluate the discomfort feelings quantitatively from perspective of human ear biomechanics. Until recently, adequate investigations on human ears, which were mainly focused on mechanic properties, sound transmission and pathology, has been done by virtue of reconstructed finite element models [2-4]. However, using ear models to interpret barometric discomfort hasn't yet been available. TM is the first receptor tissue and most sensitive to ambient pressure variations. Besides, it is responsible for absorbing pressure waves and converting it into vibration energy. Thus, it is closely linked with aural discomfort and chosen as a study objective in this paper. The purpose of this paper was to reveal the mechanism between the vibration characteristics of TM and aural discomfort, set judgment methodology and make assessment of the interior barometric environment under different running speeds in tunnels.

TM model was reconstructed based on CT scanning data from healthy volunteer with no history of ear diseases. Despite lack of uniformity of material properties [5], viscoelastic constitutive models were the most frequently explored via experiments on TM samples from cadavers [6-9]. Hence, a 7-parameter Maxwell viscoelastic model was utilized and the seven variables were derived from inverse problem-solving method and applied to our TM model, through which the model was validated. Furthermore, by exerting pressure loads at the lateral side of TM, the dynamic responses were simulated under varying pressure amplitudes and gradients. It deserves attention that the simulation conditions were conformed to Japan's air-tightness tests which uncovers the relationship between pressure changes and tinnitus for train cabin design [10]. Meanwhile, displacement, velocity and stress of TM umbo were selected as three indicators to represent its dynamics. Also, aural discomfort was divided into four levels ranging from easeful to awful by comparisons of the simulation results. In addition, interior pressure change history was collected by on-board field tests when train runs at a speed interval of 180~250km/h. The interior pressure then was loaded on TM surface and the aural discomfort it induced was analyzed eventually.

2. MATERIAL AND METHOD

2.1 TM model reconstruction

Three dimensional TM model was reconstructed in Mimics as shown in Fig.1 according to the MRI scanning data derived from healthy adult volunteer (Male, 24 years old) with no history of ear diseases. The modelling work was assisted by the collaboration with physician who has expert knowledge of the middle ear anatomy and radiation morphology, the reconstructed TM model was shown in Fig.2.

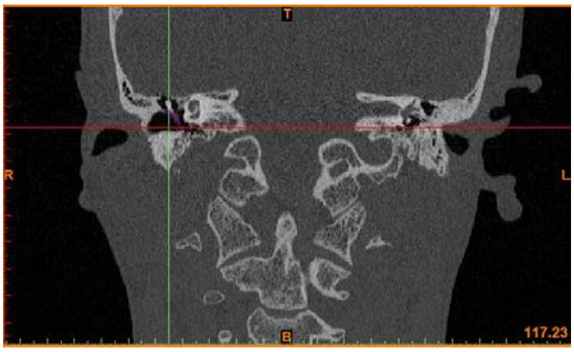


Fig.1 TM morphology and reconstruction in Mimics

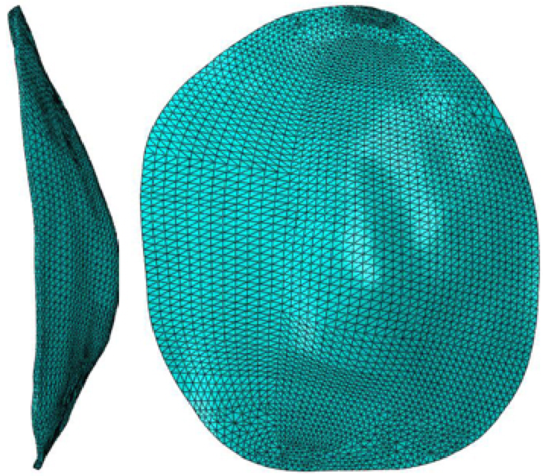


Fig.2 TM finite element model in anterior and medial view

TM is anatomically composed of three regions which are tympanic annulus (TA), pars flaccida (PF) and pars tensa(PT). PT is mostly surrounded by TA at the periphery while separated by PF at the superior of TM [11]. As is illustrated in Fig.2, TM model eliminates TA and PF on the ground that PF has slight influence on the simulation results and TA is fully clamped in simulation [6,9,12]. The thickness of TM is about 0.1mm on average and gauges 7.91mm and 9.48mm laterally and longitudinally with a cone depth of 1.54mm. Due to the non-uniform thickness distribution of TM, quadratic tetrahedral element with 10 nodes was applied and the nodes along the edge of TM was fully clamped.

2.2 Material properties for TM model

Although TM property is widely discussed [13-14], there hasn't been an agreement on which kind of constitutive model TM should be used. For biological tissue or organ, it is generally considered as both elastic and viscous. Various experiments on cadaver TMs were done to measure the viscoelastic coefficients as well as simulation methods. We utilized inverse problem-solving method to harvest the coefficients in time domain by comparison with the experimental data [9]. First, a TM strip, which gauges 1.5mm in width and 4mm in length with a uniform thickness of 0.1mm, was modeled as well as an indentation needle with a radius of 0.15mm, as shown in Fig.3.

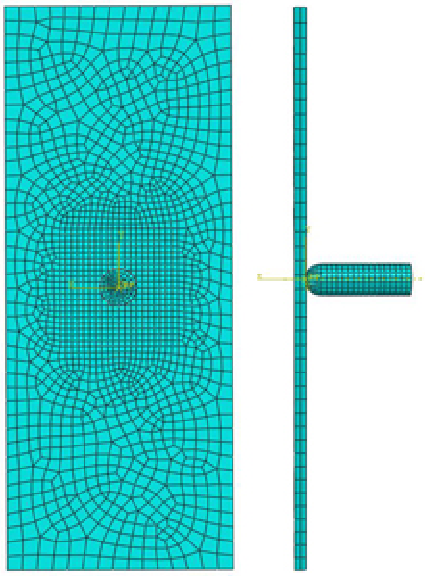


Fig.3 Indentation of needle on TM strip model

The bottom and upper surfaces of TM slice were fully clamped and the needle moves to contact TM sinusoidally at 0.2Hz. Meanwhile, a 7-parameter Maxwell model was implemented to simulate TM's viscoelasticity. Besides, genetic algorithm was employed to obtain optimal viscoelastic coefficients by controlling cost function as shown in equation 1 within 4%.

$$C = \sum_{i=1}^{N} \left\{ F_{sim}\left[d_i, \sum_{j=1}^{3} (g_j e^{-t/\tau_j} + g_\infty) \right] - F_{\exp}(d_i) \right\} \tag{1}$$

2.3 Simulations on TM model

In accordance with Japan's airtightness experiments for train [10], a series of pressure loads with varying amplitudes and gradients were created and loaded on TM surface. Furthermore, the aural discomfort was divided into four levels ranging from ideal, good, bad to worse, among which ideal level represents no hostile feelings on human ears, good level acceptable aural disturbance, bad level annoying and worse level awfully uncomfortable. Ideal level covers three conditions including 0.1-1, 0.4-0.5 and 0.3-0.5, of which the former number is pressure gradient(kPa/s) and the latter pressure amplitude(kPa), two for good level (0.2-1, 0.3-1), three for bad level (0.5-0.5, 0.4-1, 0.1-2) and four for worse level (0.1-3, 0.2-3, 0.3-3, 0.4-3). All the loads were uniformly distributing at TM surface and increased linearly. Besides, displacement, velocity and stress at umbo were selected as indicators on behalf of TM vibration with which aural discomfort level was linked.

2.4 Interior pressure data collection

Couples of on-board tests were done to record the interior pressure changes covering running speed levels of 180 km/h, 200 km/h, 220 km/h,250 km/h and 350km/h together with trains' meeting in tunnels. Fig.4 illustrates the pressure change history at different speeds.

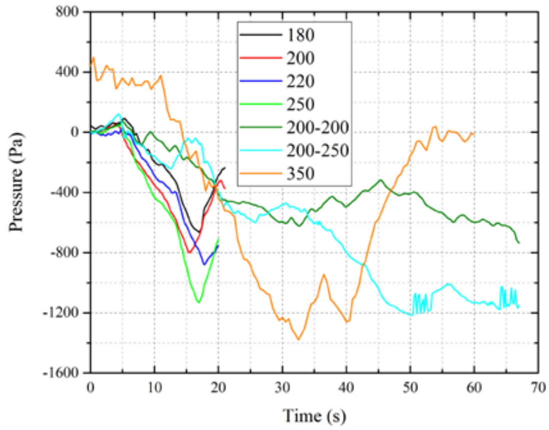


Fig.4 Interior pressure change history at different speed levels and meeting in tunnels

It should be pointed out that experiments were done in various types of tunnels but in the same train. Tests under 250km/h were completed in the same tunnel with a length of 1.05km, tests at 350km/h were done in a 5.95km-long tunnel and trains meeting tests done in 3.71km-long tunnel. For single train running in tunnel, it is visible that the interior pressure at initial stage after the train enters is positive followed by a long-term negative pressure stage and ascends when train approaches tunnel exit. With respect to trains meeting in tunnel, the interior pressure keeps negative during the whole journey. Likewise, the recorded pressure data were exerted at the lateral side of TM whose displacement, velocity and stress at umbo position were output for aural discomfort assessment.

3. RESULTS

3.1 Viscoelastic parameters for TM

Optimization achieved convergence when the cost function arrived at a value of 2.53%. The relaxation curve was displayed in Fig.5 compared with published data [9].

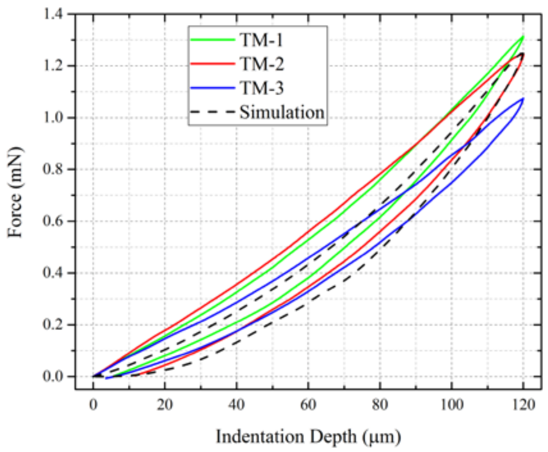


Fig.5 Comparison of relaxation curve derived from simulation with experiments

From Fig.5, it can be observed that the relaxation curve of TM shows significant viscoelastic property. The dashed simulation curve at the loading stage moves continuously within the experimental curves while at the unloading stage it goes beyond the experimental curves at the last two thirds stage. The discrepancy between simulation and experiments was considered reasonable in the light of individualities of human ears. To further justify the validity of our TM model, Fig.6 demonstrated the time-dependent relaxation modulus.

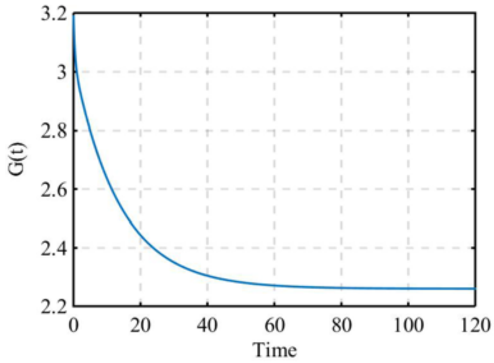


Fig.6 Reduced relaxation function of a 7-parameter Maxwell model

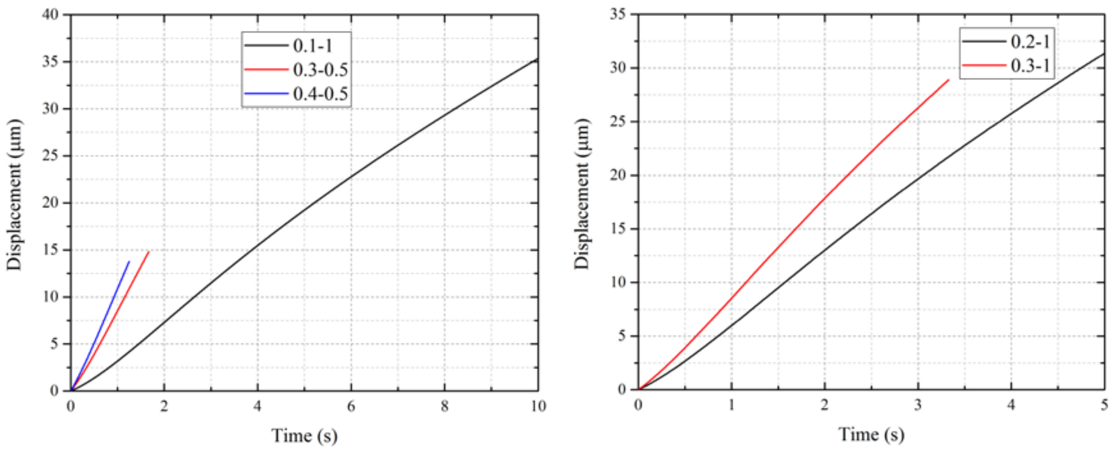
From Fig.8, the average relaxation was described by three decays. The initial decay of 4% occurs at 0.46s followed by a decay of 18% with a characteristic time 10.3s and ends up with a total relaxation of 29% with characteristic time 14.5s. Aernouts et al. has tapped into how TM thickness affects Young's modulus, which revealed that the modulus ranges from 1.74MPa to 2.87Mpa at a thickness of 0.1mm [9]. It can be seen that our steady modulus falls right in this range with a value of 2.26MPa. Hence, the simulation curve is regarded as effective despite of the disparity between simulation and experiments. Detailed viscoelastic coefficients for the model are tabulated in Table 2 below.

Table 2 Parameter values for the 7-parameter Maxwell model

	g_1	τ_1	g_2	τ_2	g_3	τ_3	g_∞
TM	0.154	0.46	0.103	10.3	0.672	14.5	2.26

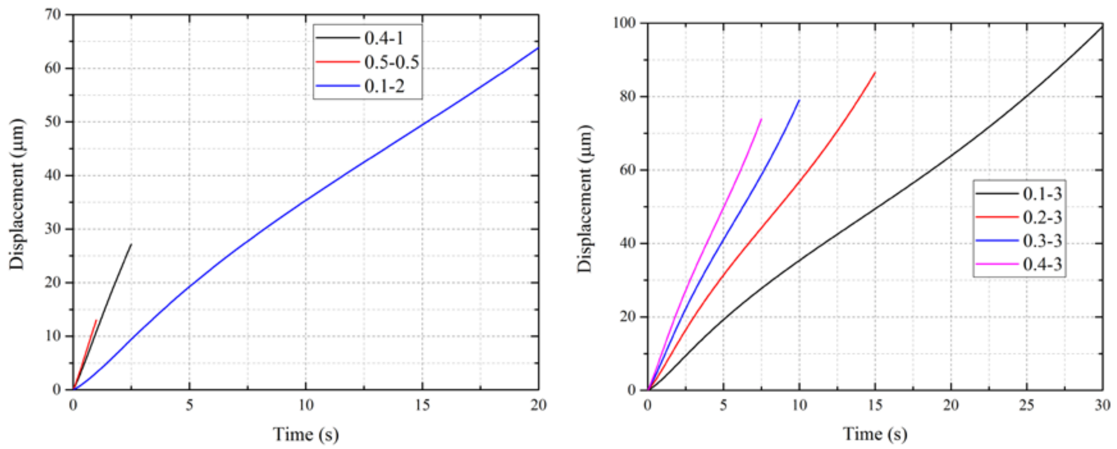
3.2 Judgement methodology for aural discomfort

Japan's airtightness tests for train has uncovered a discomfort line which divides aural discomfort into agreeable area and disturbing area. Depending on the experimental findings, we reinterpreted the discomfort line by dynamics of TM. Fig.7 and Fig.9 illustrated the output results of the three indicators under different pressure loads.



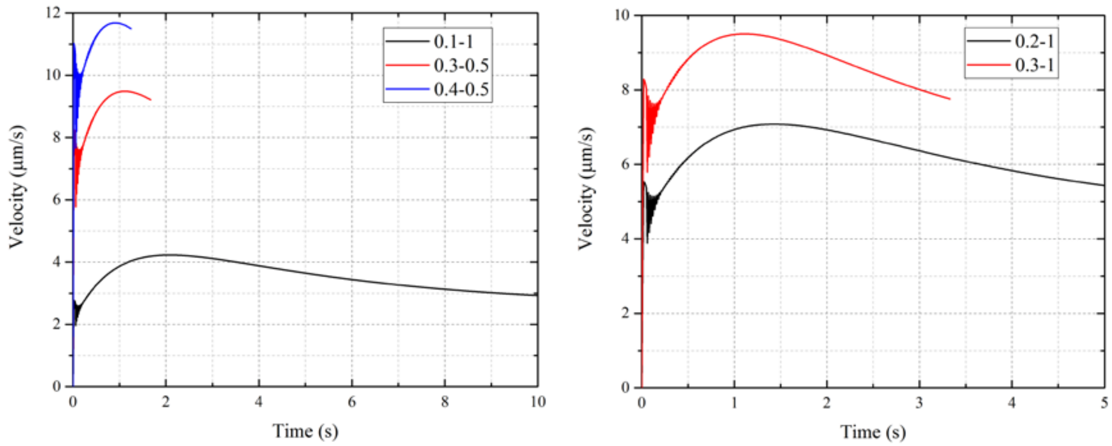
a. ideal level

b. good level

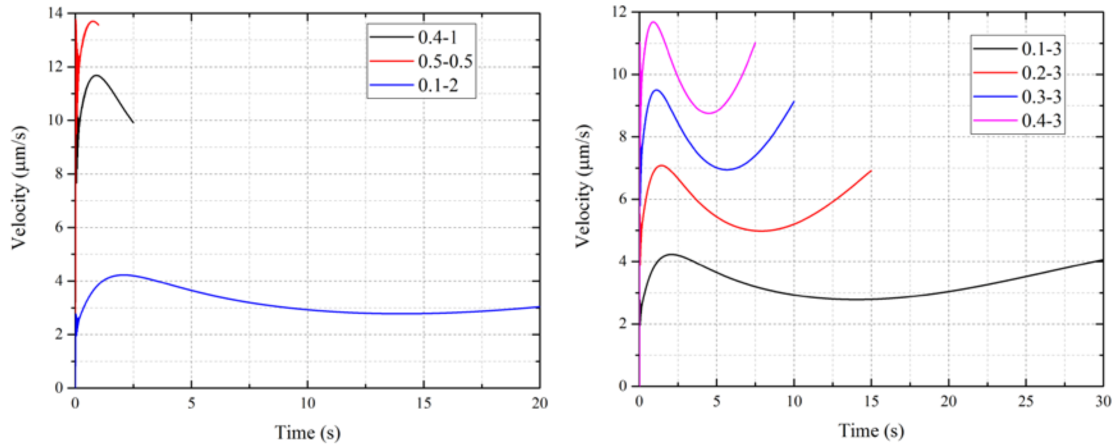


c. bad level d. worse level

Fig.7 Displacement of umbo under pressure loads from different discomfort levels

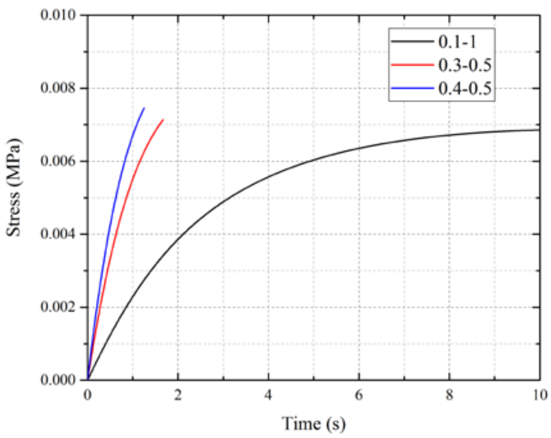


a. ideal level b. good level

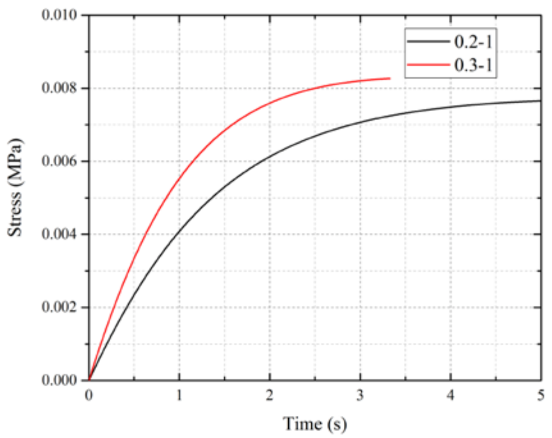


c. bad level d. worse level

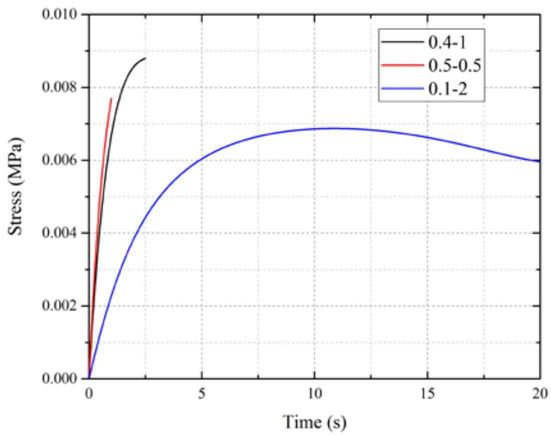
Fig.8 Velocity of umbo under pressure loads from different discomfort levels



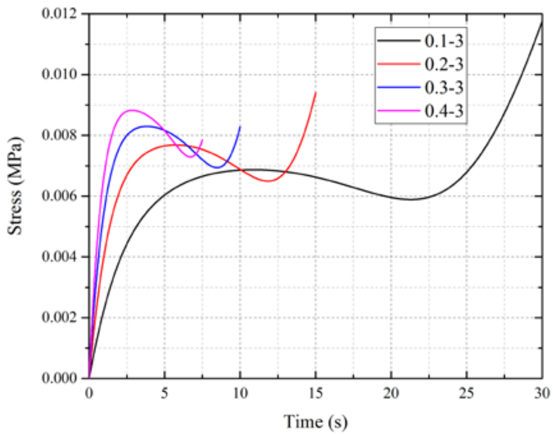
a. ideal level



b. good level



c. bad level



d. worse level

Fig.9 Stress of umbo under pressure loads from different discomfort levels

In Fig.7, it is visible that the displacement of umbo almost increases linearly and high pressure gradients generate steep ascent. The maximum values for each level are 35.35μm, 44.22μm, 63.84μm and 99.07μm respectively. In Fig.8, the velocity curves except for worse level lift sharply initially and go up moderately, then either fall or incline to stabilize after reaching amplitudes. Also, it demonstrates that high pressure gradient will produce large velocity value. Likewise, high pressure gradient also generates large stress value if the amplitudes are the same. The maximum values for each level are 0.00746MPa, 0.00827 MPa, 0.00879 MPa and 0.01177 MPa respectively. Besides, the stress of umbo tends to stabilize for long-term loading except for worse level. Moreover, the tendency of these curves justify the viscoelasticity of TM. However, it is improper to judge aural discomfort merely from indicator of velocity because it is found that the maximum velocity in ideal level is very close to that in worse level. Thus, we plotted velocity as independent variable on the X axis and displacement and stress on the Y axis respectively as shown in Fig.10 and Fig.11.

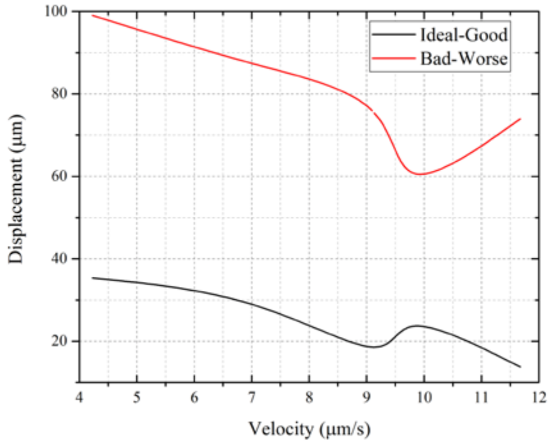


Fig.10 Velocity-Displacement curves for aural discomfort assessment

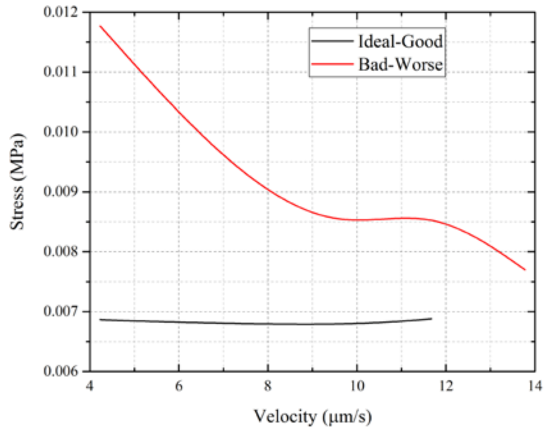
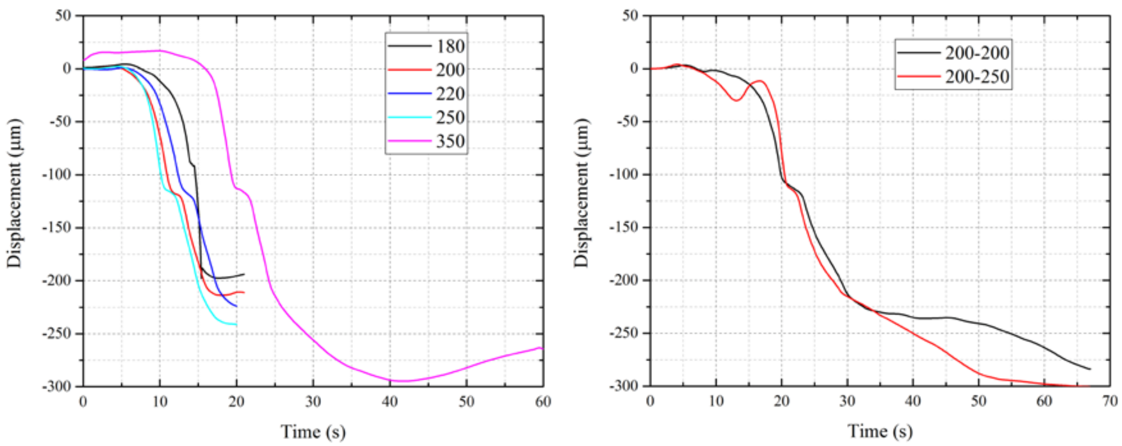


Fig.11 Velocity-Stress curves for aural discomfort assessment

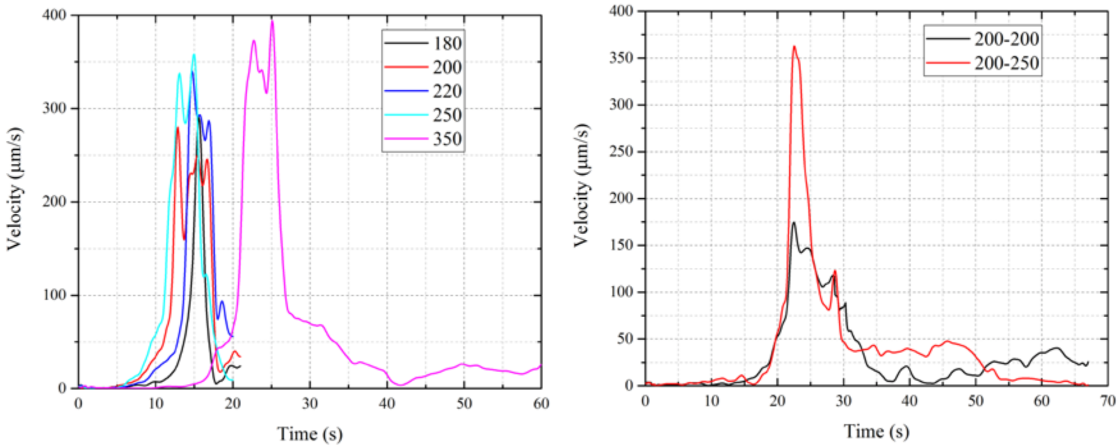
As shown in Fig.10 and Fig.11, the bottom curves represent the threshold between comfort and discomfort, above which ears generate annoyed feelings. The upper curves were plotted by the values derived from bad and worse levels. The bottom curves uncover that the threshold values for indicators of displacement and stress lower when velocity increases.

3.3 Aural discomfort assessment of interior pressure



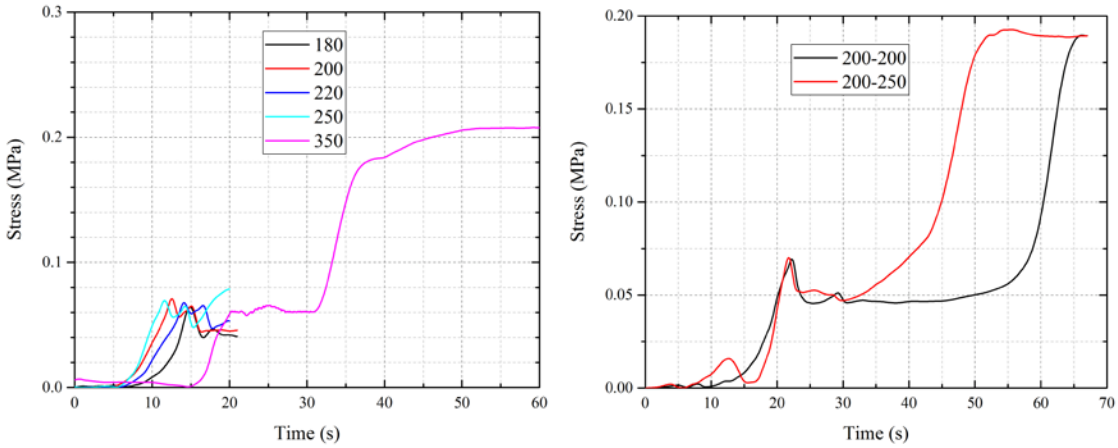
a. single train in tunnel b. meeting trains in tunnel

Fig.12 Displacement of umbo under different running conditions in tunnel



a. single train in tunnel
b. meeting trains in tunnel

Fig.13 Velocity of umbo under different running conditions in tunnel



a. single train in tunnel
b. meeting trains in tunnel

Fig.14 Stress of umbo under different running conditions in tunnel

As is illustrated in Fig.12, it presents that the displacement curves have identical consistency throughout the whole time history. When train runs under 250km/h in tunnel, the displacement of umbo initially keeps at the range of -5~13μm and drops abruptly after 10s until arrives at its minimum and goes steady, while the displacement curve bounces to ascend after reaching the valley when train runs at 350km/h. With respect to trains meeting conditions in tunnel, the displacement curves decrease slightly before 15s and falls sharply afterwards till 35s and 50s separately, after which the curves decrease mildly. In Fig.13, the velocity curves lie under 4μm/s at the beginning followed by a sudden ascent and descent, after which they calm down. In Fig.14, the curves also go with a low value and climb steeply to about 0.065MPa. When train runs at 350km/h or trains meet in tunnel, the stress curve climbs again and stabilizes until the train departures. In general, the maximum values of the three indicators increase with the lift of running speed.

4. DISCUSSION

When train enters the tunnel, the air is compressed and propagates in the form of compression wave at sonic speed, which forces the pressure in the tunnel increasing. As the wave arrives at the tunnel exit, a new type of wave generates and returns to tunnel in the form of expansion wave, which in turn make the pressure fall. Under the alternating effect of the two wave types, the pressure inside the tunnel fluctuates up and down. The altering pressure in the tunnel travels into the cabins by path of openings of the train. Regarding to single train running conditions as is illustrated in Fig.4, the recorded interior pressures stay positive initially followed by a negative stage and go up till the train leaves. Whereas the interior pressure continues to decline after a short stage of positive pressure for meeting conditions. In addition, it indicates that higher running speed brings larger pressure amplitudes either for single train running condition or for trains meeting condition.

Aural discomfort induced by interior pressure fluctuations when train passes through tunnels hasn’t been adequately reported until recently. In generally, aural discomfort or ear trauma is mainly attributed to time-dependent transient pressure or frequency-dependent noise [15-20]. As is reported in explosion about ear injury, blast wave generates a short-lived positive overpressure initially and is prolonged by a long-term negative stage [15,21]. Virtually, the recorded interior cabin pressure is much analogical to the blast wave in pressure change characteristics. Nonetheless, blast wave differs in pressure amplitude and duration from interior pressure, whose amplitude is far lower but the time history is much more long-lasting than blast wave. Hence, blast injury is commonly manifested in TM rupture, ossicles dislocation and tinnitus. What deserves attention is that TM penetration is the most frequently diagnosed ear trauma patterns. And it is caused by overpressure in the ear canal, which was verified by otoscopic observations that patients have inverted edges of the penetration [15-16]. On the other hand, barotrauma reported in aviation is also somewhat analogical to train-tunnel effect. Cabin pressure in aircrafts alters with ascent and descent maneuvers, which is accompanied with varied degrees of ear ailments [22-23]. Researches on barotrauma reach a consensus that descent poses much higher risks on passengers than ascent, that is, positive pressure differential between ear canal and tympanic cavity is more likely to cause ear complaints than equal amount of negative pressure differential [24]. Mirza et al uncovered that ET opens passively to expel excessive pressure in the tympanic cavity when the pressure differential reaches a threshold of 15mmHg (2kPa), but ET may stops working if middle pressure is lower than ambient pressure [25]. These findings on ear complaints caused by blast and aviation offers important referential values for assessment of tunnel-induced aural discomfort.

As is illustrated in Fig.4, the lowest amplitude of the interior pressure is -1.4kPa which isn’t enough to force ET opening. Hence, it is futile to balance the pressure differential between sides of TM neither by opening of ET itself nor by any physical maneuvers like swallow or yawning. It can be interpreted that human ears have to confront with the hostile barometric environment without any conscious actions of relief unless air tightness of train is improved. Regarding to single train in tunnel, the amplitudes of the three indicators lift with the increasing of running speed, which implies higher travelling speed in tunnel incurs more terrible aural feelings. Additionally, the curves of the three indicators display some common characteristics. For short tunnel to travel, there is a peaceful stage lasting for 8 seconds right after the train enters. After this stage, one abrupt change appears representing by sudden drop of displacement and peaks of velocity and stress. During this stage, human ears perceive a significant pressure shock at the first half stage and attenuate at the second half until the train leaves. Whereas for long tunnel, the peaceful stage for ears is prolonged to about 18 seconds after which also follows with a pressure shock for ears. As the train runs, the aural discomfort continues to worsen until it departures. With respect to trains meeting in tunnel, the former 18 seconds also offers a friendly environment for ears and then ear complaints generate. It is noteworthy that meeting speeds of 200km/h versus 250km/h results in more awful aural feelings than that of 200km/h versus 200km/h. In general, it is conclusive that the whole course of train's passage can be divided into two stages. One is a pleasant process for human ears sustaining for several seconds and the other is dominated by a much unfriendly pressure environment for ears.

Judging from displacement of umbo, it indicates that the TM bulges inward initially and dents outward gradually until the train leaves. As a result of the leverage effect of ossicle bones, the energy received by inner ear is amplified for times [2]. Hence, discomfort feelings perceived by TM can also transfers to inner ear by way of ossicles and the discomfort level lifts as well. Furthermore, it is likely to infer that human ears may generate varying levels of otalgia, vertigo or tinnitus as the curves of the three indicators display. We enquired all the testers after the tests completed. Most of them complained the otalgia when train runs in tunnels, and some reported tinnitus symptoms. Nonetheless, it isn't straightforward that whether tinnitus is caused by interior pressure change or by booming noise or unified effect of both. Further investigations will be conducted to identify the true causations of tinnitus.

5. CONCLUSION

Train's entering into the tunnels will change the previous air flow field and make interior pressure fluctuate as well, which brings varying degrees of aural discomfort. For purpose of finding a way to assess aural discomfort quantitatively, a TM FE model was reconstructed based on volunteers' CT scanning data of temporal bone. To solve the problem of non-uniformity of TM material properties, TM was assumed to be viscoelastic in time domain and to satisfy a 7-parameter Maxwell model with a Poisson ratio of 0.499, because this assumption was verified to be conducive to reach convergence for cost function. Meanwhile, inverse method was employed to obtain the optimal values of the 7 parameters by genetic algorithm. Furthermore, dynamics of TM, which is represented by indicators of displacement, velocity and stress of umbo, was simulated under different barometric conditions which is in accordance with published air tightness tests. Through ranking aural discomfort into four levels and comparing the output curves of the three indicators, a set of methodology was established to judge aural discomfort. On the other hand, a series of on-board tests were conducted to collect the history of interior pressure change when trains pass through tunnels or meet in tunnels at different running speed. The recorded pressure data was exerted on the lateral surface of TM and the simulation results of the indicators were output.

The simulation results indicate that the maximum values for the four levels from ideal to worse are 35.35μm, 44.22μm, 63.84μm and 99.07μm for displacement and 0.00746MPa, 0.00817 MPa, 0.00879 MPa and 0.01177 MPa respectively. It also reveals that there exists a peaceful stage during which human ears feels pleasant. However, this sustains 15 seconds at the best and alters with variations of running speed and tunnel shape. A pressure wave shock is experienced for ears right after the peaceful stage terminates and ears begins to perceive awfully disturbed accompanied with otalgia, vertigo or tinnitus. This annoyed feeling lasts as long as the train departures the tunnel exit. It deserves attention that aural experiences differ significantly with regard to tunnel length, because of differences of interior pressure change history.

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