Investigation on Passenger Comfort during HST Operation using a New App for Smartphones

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ABSTRACT
The interior aerodynamic pressure generated by train operation will bring passengers comfort problems. To better evaluate the feeling of passenger cars during real operation, a new App was designed. Using this App and based on a CRH380B high-speed train, it conducted a field investigation on pressure comfort. The results show that the evaluation test by using the App has good repeatability. Although there are individual discrepancies in the assessment process, the moment of passenger discomfort is concentrated, which is mainly in the first half of the tunnel operation and in the recovery phase after train exiting the tunnel. The discomfort of these two stages is caused by different reasons, resulting in different profiles of the recording discomforts. On 3s and 1s scales, there is a correlation between the interior pressure variations and the passenger discomfort, but the two have a certain delay. Swallowing action can offset pressure changes, so that reduce the discomfort level.

Key words: Passenger comfort, App, High-speed train, Aerodynamic pressure, Field study.

1. INTRODUCTION

In the HST (high-speed train) operating process, the pressure on train surface is intense and complex\(^1\). This pressure will penetrate into compartments through gaps, causing changes of interior pressure. This pressure changes impact directly on the passenger's outer ear. Because the middle ear separated by the tympanic membrane still maintains the original pressure at the
same time, a differential pressure occurs on the two sides, resulting in uncomfortable feelings of passenger’s ears\(^2\). In 2016, the China Railway Corporation operated 2,595 high-speed trains, accounting for about 60 percent of all global high-speed trains, and with a ridership exceeding 1.44 billion in the year\(^3\). Therefore ensuring the safety and comfort of passengers has become particularly important. Many scholars have done a number of meaningful works in the relevant fields.

Grothrowpe investigated pressure effect in tunnel and introduced the influence of pressure wave on ear and corresponding comfort criteria; he indicated that the standard reflects the way in which the normal ear can periodically relieve the pressure difference\(^4\). Schwanitz et al. furtherly conducted a questionnaire survey, a laboratory experiment, and a field measurement by using slider or retrospective assessments, the results show that amplitude/time combinations lead the ear discomfort and pressure events of the recent past significantly influenced current discomfort \(^5\)\(^6\). Passenger comfort is an abstract concept that requires specific quantification; Sanok et al. divided passenger comfort into seven levels and used the seven-point rating scale to investigate the influence of noise on pressure comfort.\(^7\). Tunnel length plays an important role on passenger comfort. Mei et al. analyzed pressure changes in very long tunnels by one-dimensional calculation, and proposed that comfort criterion in tunnels should be considered in multiple time intervals \(^8\). By conducting a field test, Liu et al. investigated the influence of tunnel length on passenger comfort based on interior pressure \(^9\).

In the previous studies, passenger comfort mainly comes from the comparison of indoor pressure with relevant standards, which neglects the individual differences; the investigation on the real feelings of passengers in the operating state is much less. The current researches on passengers utilize an exclusive device Slider, which number and operating space is limited, while the questionnaire and retrospective assessment lack of real-time and accuracy. There are challenges in the investigation of ear discomfort. However, the actual experience of the passengers during train operation is precisely the basis for improvement that should be preceded by HST manufacturing and operating departments in the future, therefore the relevant methods and related research needs to be added.

This article introduces a new App for evaluating pressure comfort. By using the App, a field test on passengers was conducted on a CRH380B high-speed train. The second section is about App design, the third segment describes the test details, and the fourth part is the test results. This article provides significant reference to improving the operational quality and ensuring passenger comfort.
2. APP DESIGN

Existing passenger comfort evaluations are carried out by using special equipment, which are limited in terms of quantity, space or accuracy. Due to the popularity of smartphones, investigation on passenger comfort can be conducted based on the personal phones, which will reflect individual differences and not be limited by space and quantity. Based on this, a new smartphone App "Evaluation System of Passenger Ear Comfort" was designed and produced. The purpose of the App is using the method of passenger entity subjective report to carry out data collection and research.

The App is developed based on Android and IOS two operating systems, and the user interface is shown as Fig.1. Because passenger's age, body condition will cause differences in the ear pressure perception [5], which in turn affects the unity of variables, these information needs to be noted for distinction. Therefore, a user information area, Area A, is designed. The main information in this area includes the “name”, “age”, “stayed up last night”, etc. In addition, subjects can input more useful information in the name box.

In order to clearly quantify the passenger's sense of pressure discomfort, the discomfort feeling is divided into seven levels (i.e., 0 ‘not at all’, 1 ‘slightly’, 2 ‘moderately’, 3 ‘fairly’, 4 ‘very’, 5 ‘awfully’, and 6 ‘extremely’ uncomfortable) in Area B. This seven-point rating scale is similar to that in the investigation [7]. Area B consists of a slider operating unit and a display unit. Subjects can drag the slider to realize the real-time recording function in the test process.

As the data collection process is separately operated by subjects on their personal mobile phone, the back-end cloud server platform is designed for data aggregation and post-processing. Correspondingly, the basic control area, Area C, is designed in App, which mainly includes three operation buttons: “Start”, “Upload” and “End”. The “Start” button controls the beginning of the recording, and recorded discomfort data are locally stored in the personal phones. “Upload” button controls data to be uploaded to the back-end cloud servers by the front-end App on mobile phone. The “Upload” button does not interrupt data acquisition. The “End” button controls terminating the data acquisition process and the data will be uploaded at the same time.

Since the time of this App is consistent with that of the mobile phone system, the automatic timing function of each mobile phone makes the time of every participants in evaluation process always synchronized. A timer was added in the lower right-hand corner of the interface to unify the test duration.
3. TEST DETAILS

The evaluation test is based on CRH380B train model (Fig. 2), which operational speed is 300km/h. Due to the difference of interior pressure among carriages [8], the total test was conducted in No.1 carriage. The test line is selected in a certain section of Hengyang-Lechang high-speed rail line, the operational direction is single and southeastern.

Since the pressure waves in HST compartments is in state of transient change, pressure sensors with a good sensitivity and a wide measuring range are required for the capturing the characteristics of transient pressure. In this test, two LL-250-15A sensors produced by Kulite Semiconductor Inc., with measurement range up to 103.24 k Pa and sensitivity 9.69 mV/10 kPa (from LL-250-15A specifications), were selected and deployed on interior surface of No.1 carriage. The height of sensors location is 1m from the ground of compartment, as shown in Fig.3, which reflects the pressure characteristics on outer ear of test subjects. A multi-channel device, C1, produced by IMC Inc., was used for pressure data acquisition and storage. The sampling frequency is 200Hz and the filter frequency is 50Hz, which meets the EN standard [10].

In test process, each subject uses a smartphone. At first, they accomplish the
information input in the Area 1 of the App, then operate the Area 3 to start the test simultaneously, then slide the slider in the Area 2 to keep their actual feelings real-time recorded, and finally operate the Area 3 to terminate the test and upload the experimental data.

4. RESULTS AND DISCUSSIONS

4.1 Method validation

In order to ensure the accuracy of interior pressure measurement, the results from the two interior sensors are compared in Figure 4. These two curves have a good consistency. The largest discrepancy occurs at 305.455s, with a difference of 3.9%. So the interior pressure results are accurate and reliable.

Considering the air tightness of HST has a direct impact on passenger comfort, three repeated tests were conducted on one HST to ensure the repeatability of the experiment, and the results are shown in Figure 5. The actual operational speed maintained at 297 ~ 304km / h during the test. So there is certain difference in the x-axis direction among the three curves, which makes changes on a few positions of passenger discomfort (i.e., 2s in advance or lasts longer). This is related to the random and operating factors among the three trials. However, summarizing three tests, the location of the uncomfortable feeling is roughly the same with the corresponding position of the interior pressure curve, and the discomfort level is the same for most of the time. Therefore the experiment has a good repeatability and the methodology is reliable.

Figure 4. Comparison of two sensors in the first test. Figure 5. Time histories of interior pressure and corresponding discomfort level in three tests.

4.2 Discomfort in different individuals

Individual difference is a noticeable factor in assessment experiments. Figure 6 shows the uncomfortable feelings recorded by the four participants and the pressure measured in the carriage throughout the first test. The No.2
subject (S2 in the figure) recorded “stayed up last night” phenomenon, other three subjects did not have this record. From the figure, the moment of uncomfortable feeling is more concentrated, such as discomfort level 2 or more of four subjects is mostly recorded in the range of 46-95s and 300-475s. Discomfort of level 3 or more occurs at the similar moment, which is before or after the first valley of internal pressure when the train just entered the tunnel. The interior pressure drops quickly at this time because outdoor expansion wave, generated by train tail entering the tunnel, penetrates into carriages and induces expansion effect, forming a pressure difference between passengers’ outer and the middle ears [3], therefore leads to increased ear discomfort levels. No.2 subject (S2) has the only level 4 discomfort at 306 s in the total test, which sustains 3s. Compared to the other three subjects at this time, the reaction of S2 is more intense, which may be relevant with the “stayed up last night” phenomenon: poor rest makes people more sensitive to pressure. In addition, the S2’s discomfort level 3 at 399s and level 2 at 452s are advanced compared with the locations of other three subjects, which may be also related to the lack of rest.

Figure 6. Discomfort of four subjects and corresponding interior pressure in the first test.

4.3 Correlation between discomfort and interior environment

Because the results among different individuals in Fig.6 exist commonness, in order to further explore the correlation between passenger discomfort and interior environment of the train, take the frame region of the most concentrated discomfort in Fig. 6 and the result of subject 1 (S1) for detailed analysis.

Figure 7 shows the time histories of interior pressure in the frame region with the corresponding discomfort record. There are 5 tunnels in this region, including a long tunnel Danshuiling Tunnel (2203m) (the portals are marked with two black dashed lines) and four short tunnels T1, T2, T3, T4 (length from
91-214 m, marked by a purple frame). That a train passes through the long tunnel causes a significant change in the interior pressure, whereas train passing through the short tunnels only causes a slight fluctuation of pressure and will not change overall trend of interior pressure. Therefore, in the long tunnel, the passenger discomfort is directly related to characteristics of the waveform; short tunnels do not significantly affect the human ear experience, only bring a slight pressure sense at 76s and 80s.

In addition, for the moment after the train just exiting the long tunnel, that is 63s, a level 2 of discomfort appears and lasts 3s. This is because the indoor pressure reaches a lower value of point “P” during the tunnel process; when the train exits the tunnel, exterior pressure of the train is instantly changed from negative to environmental value, so that a large differential pressure between indoor and outdoor environment is formed instantaneously; the interior pressure rapidly increases towards the exterior pressure value, resulting in ear discomfort. After a period of time that train exited the tunnel, a clear ear discomfort level 3 appears at the 89s and lasts 3 seconds. It is worth noting that this profile of discomfort is unique, showing a stepwise increase in the level, as marked with L₁, L₂ and L₃ in the Figure 7. This is due to the function of the train airtightness: the interior pressure has transited from the rapid change A₁ to steady increase A₂, the latter brings the pressure on passenger eardrum accumulated gradually, so the discomfort level is also increased gradually from low to high. This discomfort is relieved by swallowing action (92s), and ultimately disappears (100s) by pressure reaching a balance between outer and middle ears.

Figure 8 reveals time histories of pressure variation on 3s scale (peak-to-peak value in a 3s period) and corresponding discomfort record on 3s scale (maximum level in a 3s period). The maximum peak of 3s pressure variation (P₁) appears at 41.8s, with a value of 325.75 Pa. This is because the exterior expansion wave penetrates into passenger compartments (as described in Section 4.2) and induces interior pressure decreasing rapidly. Influenced by this drastic pressure change, passenger experiences a discomfort (on 3s scale) of level 3 at 45s. The second peak P₂ appears at 52.5s, with a value of 315.63 Pa. At this point the subject just conducted the swallowing action, which makes the pressure of outer and middle ears re-balanced and thus offsets the pressure change of P₂, resulting passenger discomfort is reduced to level 1. The third peak of 3s pressure variation (P₃) appears at 58.9 s with a value of 309.31 Pa. This peak of pressure change exerts stress on the outer ear, bringing the level of discomfort rise at 61 s. At the stage after the long tunnel, there is no equivalent peak (more than 300 Pa), but still appears discomfort of level 3. This interesting phenomenon is dedicated by extreme change of pressure magnitude in a long time period, and verifies the opinion about train airtightness for Fig.7. This reason is totally different with the one for
discomfort in the tunnel stage (drastic change of pressure in short time), thus the two profiles of discomfort is different.

Figure 9 shows time histories of pressure variation on 1s scale and corresponding discomfort level. Similar to the that on 3s scale, the first peak $P_1$ on 1s scale, 189.37Pa, brings discomfort of level 3 at 47s; the effect of second peak $P_2$ is weakened due to the swallowing action at 1s before; the third peak $P_3$ brings a followed-by level 2 discomfort at 63s. The difference from 3s scale lies that: two new peaks appear along the curve of 1s pressure variation, which are $P_4$ (with a value of 101 Pa at 73.62 s) and $P_5$ (with a value of 113.62 Pa at 79.1s). Accompanied with these two peaks, two uncomfortable feelings (level 1) occur at 76 s and 80 s, respectively. This short-term level 1 feeling is much slighter than the discomfort of level 3, however, it does reveal the reason why the short tunnels (corresponding $T_1$ $T_2$ frames in Figure 7) bring passenger ears slight discomfort: in short tunnels, there are significant pressure changes within a short time period.

5. CONCLUSIONS

This article introduces a new App aiming at passenger comfort evaluation. Based on CRH380B high-speed train, a field test was conducted by using the App. The conclusions can be drawn as follows:

1. The field test of the ear comfort evaluation with the App has good repeatability
2. It is similar in locations of discomfort among all subjects, which mainly concentrates in the first half of the tunnel section and the stage after train exiting the tunnel.
3. The passenger discomfort after train leaving the tunnel needs the equivalent attention with the discomfort in tunnel; the degree of two discomforts can both reach the "fairly uncomfortable". However, the reasons for the two stages of discomfort are different: that in the tunnel is due to the short-term rapid changes of pressure, and that after the tunnel is because of a gradually
increased magnitude of pressure in long time, leading the profile of two discomforts is also different.

4. Pressure variation on 3s and 1s scale can well reflect the condition of passenger comfort, but the discomfort events have some hysteresis to peaks of pressure variation. Swallowing action can offset the impact of interior pressure changes on the ear, and can ease a certain levels of discomfort.

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REFERENCES

1. Liu, T. H., Chen, Z. W., Chen, X. D., Xie, T. Z., & Zhang, J. 2017. Transient loads and their influence on the dynamic responses of trains in a tunnel. Tunnelling and Underground Space Technology, 66, 121-133.

2. Suzuki and Hiroa. 1999. A Review of Research Trends on Passengers’ Aural Discomfort Caused by Rail Tunnel Pressure Change. Foreign rolling stock, 5, 004.

3. “China puts nearly 2,600 high-speed trains into operation by 2016” - news.xinhuanet.com. Retrieved 2017-07-02.

4. Gawthorpe, R. 2000 Pressure effects in railway tunnels. Rail International, 4, 10-18.

5. Schwanitz, S., Wittkowski, M., Rolny, V., and Basner, M. 2013. Pressure variations on a train–Where is the threshold to railway passenger discomfort?. Applied ergonomics, 44(2), 200-209.

6. Schwanitz, S., Wittkowski, M., Rolny, V., Samel, C., and Basner, M. 2013. Continuous assessments of pressure comfort on a train–A field-laboratory comparison. Applied ergonomics, 44(1), 11-17.

7. Sanok, S., Mendolia, F., Wittkowski, M., Rooney, D., Putzke, M., and Aeschbach, D. 2015. Passenger comfort on high-speed trains: effect of tunnel noise on the subjective assessment of pressure variations. Ergonomics, 58(6), 1022-1031.

8. Mei, Y., Zhang, C., Zhou, C., Jia, Y., and Wu, M. 2015 (in Chinese). Research on the aural discomfort when a single train passes through a super long tunnel. Journal of Mechanical Engineering, 51(14), 100-107.

9. Liu, T. H., Chen, X. D., Li, W. H., Xie, T. Z., Chen, Z. W. Field study on the interior pressure variations in high-speed trains passing through tunnels of different lengths. Journal of Wind Engineering and Industrial Aerodynamics, 169, 54-66.

10. BS EN 14067-5:2006+A1:2010 Part 5: Requirements and test procedures for aerodynamics in tunnels.