Characteristic analysis of air pressure wave generated by high-speed trains traveling through a tunnel

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Abstract: It is a complicated dynamic phenomenon when a transient pressure pulse is triggered by two high-speed trains passing each other in a tunnel. The air pressure pulse is a transient excitation to side wall of the car body. It can stimulate almost all vibration modes of the car body and the correlated assemblies, cause serious aerodynamic noise, and have important impacts on car body distortion, train noise, and operation safety. This article analyzes the time-frequency characteristics and main parameters of field-measured the air pressure wave, and its relationship with the train velocity as well as the vibration of the car body. Cepstrum analysis concludes that in the process of the meeting, the air pressure wave in tunnel crossing is a multiplying pressure wave instead of a superposed wave. The pressure pulse during the meeting is non-symmetrical one featured with a sharp front, large amplitude, fluctuating central section, and less sharp tail. The pulse width is inversely proportional to the train speed. As the speed increases, the impulse amplitude is amplified, and the speed of pulse front is advanced.

Key words: high-speed train; air pressure pulse; transient excitation; modes of vibration

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1. Introduction

When two high-speed trains pass each other in a tunnel, under the action of high train-induced wind, the instantaneous pressure pulse is triggered between the meeting sides of car bodies due to the sudden reduction in headroom section. Then, the pressure wave fluctuates. At the end of meeting, the sudden amplification of headroom section produces a new pressure pulse, and eventually the pressure wave resumes to its original state. Tian et al. [1] investigated the effects of the instantaneous pressure pulse on the car body and the side window, and found that the pulse peak value was about 3 times the initial pressure wave value. When a single train traveled through a tunnel, however, the positive amplitude of the generated pressure wave was almost equivalent to the negative one [2]. Numerical calculation showed [3] that the negative pressure had the most drastic change between 11 and 13 s when two high-speed trains met in a tunnel. The ORE's (Office for Research and Experiments of the International Union of Railways) report [4] indicated that the maximum amplitude of the pressure wave during the meeting of two trains was 2.8 times that of one train operation. In the

aerodynamic experiment of double-deck container train through a tunnel, the pressure wave at the meeting side of the car body was 16% larger than the other side [5]. As for the CRH2 (China Railway Highspeed 2) at the speed of 250 km/h, the pressure wave on the car body reached a peak value of 1 195 Pa, and at the speed range of 300–350 km/h, the peak of the pressure wave was 1.3–1.8 times larger compared with the case of one train operating at the same speed [6].

The pressure wave generated in the process of two trains passing a tunnel is a transient excitation and has broad frequency bandwidth, which can stimulate almost all vibration modes of the car body and the correlated assemblies. Thus, it may cause serious aerodynamic noise, car body distortion, and train noise, and jeopardize safety.

Based on the vibration and air pressure data collected in the operation of Wuhan-Guangzhou high-speed passenger motor train unit, the paper uses signal processing techniques to analyze the properties of the pressure wave generated by high-speed trains passing through a tunnel.

2. Cepstrum analysis of pressure waves

According to the analysis of the pressure wave of one train [2], the negative pressure wave is relatively simple. Fig. 1 reveals the measured pressure wave on the car body of Wuhan-Guangzhou high-speed passenger motor

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(a) The pressure wave when one train is in operation

(a) The measured pressure wave

(b) The tunnel wave when two trains meet

(b) Cepstrum of the measured pressure wave

Fig. 1 Pressure waves measured on the car body of Wuhan-Guangzhou passenger high-speed motor train unit

Fig. 2 Cepstrum analysis of the measured pressure wave

train unit that corresponds to two cases: (a) one train is in operation and (b) two trains meet. In Fig. 1(a), the negative pressure amplitude is roughly the same as the positive one.

The pressure wave in a tunnel is assumed to be a superimposed wave which consists of extruded wave, reflected wave and so on. The cepstrum analysis of the measured pressure wave is performed by [7]:

$$\begin{aligned} x(t) &= s(t) * h(t), \\ \ln |X(\omega)|^2 &= \ln |S(\omega)|^2 + \ln |H(\omega)|^2, \end{aligned} \quad (1)$$

where $s(t)$ is import signal, $x(t)$ is output signal, and $h(t)$ is impulse response; $S(\omega)$, $X(\omega)$, and $H(\omega)$ are corresponding frequency response functions. The results of cepstrum analysis are shown in Fig. 2. There are obvious echoes, especially at 9 s. Echoes and wave source take the form of convolution at the measured points, showing that the tunnel pressure wave contains a multiplying wave rather than a superposed wave during the meeting.

3. Characteristics of pressure pulse

Fig. 3 is the measured pressure pulse at the speeds of 300 km/h and 350 km/h. Vacuum between two car bodies increases in an instant, and negative pressure pulse that is similar to a rectangle in shape is formed. It is observed that the wave top fluctuates and inclines, due to the insufficient frequency response width of sensors [8-9]. Net increase of pressure during the meeting ranges between 0.5 and 1 kPa, which induces gas-solid coupling vibration [10], and has non-negligible effects on car body distortion, noise and operation safety.

3.1. Time domain characteristics

The air pressure wave generated by high-speed trains meeting in a tunnel is in fact a complicated pulse excitation. The parameters of the pressure wave [11] in Fig. 3 are shown in Table 1. The measured pressure pulse is complicated due to noise interference. In practice, the point at the median of the amplitude (50% amplitude point on pulse edge) is used as a reference. The pulse

width and rising time at the point of 50% amplitude are relatively stable and representative.

According to the parameters in Table 1 and Fig. 3, the pressure wave presents the following characteristics:

(1) The pulse width is inversely proportional to the speed of trains; with the increase of speed, the transient response sharpens.

(2) The pulse amplitude increases with the speed.

(a) At 300 km/h

(b) At 350 km/h

Fig. 3 The measured pressure pulse at different speeds

Table 1 Pressure pulse parameters during the meeting of two trains in tunnel (not net increased value)

Pulse parameter	350 km/h	300 km/h
Pulse amplitude (kPa)	-3.81	-1.15
Pulse base amplitude (kPa)	-2.06	-0.29
Median amplitude (kPa)	-2.93	-0.72
Pulse width (s)	1.026 6	1.291 4
50% rise time (s)	0.092 2	0.108 2

(3) As train speed rises, the increase of the pulse amplitude accelerates and excitation frequency band widens.

(4) The pressure pulse is asymmetric.

3.2. Frequency domain characteristics

The air pressure pulse is approximately rectangular in shape which is set as follows:

$$x(t) = \begin{cases} 1, & |t| < T, \\ 0, & |t| > T, \end{cases} \quad (2)$$

where T represents the duration of pulse (pulse width), The Fourier transform of rectangular pulse is [12]:

$$X(\omega) = \int_{-T}^T e^{-j\omega t} dt. \quad (3)$$

Discrete Fourier transform (DFT) is used to calculate digital spectrum [13]:

$$G(k) = \frac{1}{N} \sum_{n=0}^{N-1} x(n) e^{-j \frac{2\pi kn}{N}}, \quad (4)$$

where $G(k)$ is DFT spectrum, $x(n)$ is the time series of the pulse, and N is data length. As single pulse is non-periodic and its Fourier spectrum is continuous, we use repetitive surge oscilloscope (RSO) [13] to produce the frequency spectrum of a periodic impulse wave (see Fig. 4). The oblique line shows the attenuation of standard rectangular pulse. This frequency spectrum has following features:

(1) The Fourier spectrum of the pressure pulse has similar characteristics to a rectangular pulse, and the attenuation is close to 20 dB/decade.

(2) The pressure pulse contains high frequency excitations, and its top fluctuates violently and the attenuation rate is lower than that of a typical rectangular pulse.

(3) The energy of frequency spectrum mainly distributes in 0–20 Hz attenuated to -40 dB.

Fig. 4 Fourier spectrum of the pressure pulse in tunnel produced by RSO

4. Excitation effects acted on car body by pressure pulse

4.1. Shock response spectrum

For a system of one degree freedom, the relationship between the maximum response and the natural frequency, when the shock pulse is applied, is called shock response spectrum [11]. In order to examine the excitation function of the pressure pulse, a unit of car body is separated, and its impact response spectrum is analyzed after normalization and adjusting damping ratio.

If a step shock is applied, the response is:

$$\frac{x(t)}{F_0} = A(t) = \frac{1}{k} \left[1 - \frac{e^{-\zeta \omega_n t}}{\sqrt{1-\zeta^2}} \cos \left(\omega_n \sqrt{1-\zeta^2} t - \psi \right) \right], \quad (5)$$

$$S_a(\omega) = \left| \frac{\omega_d}{m} \int_0^t f(\tau) e^{-\zeta \omega_d(t-\tau)} \left[\left(\frac{1-2\zeta^2}{1-\zeta^2} \right) \sin \omega_d(t-\tau) + \frac{2\zeta}{\sqrt{1-\zeta^2}} \cos \omega_d(t-\tau) \right] d\tau \right|_{\max}. \quad (8)$$

4.2. Response spectrum analysis of the pressure pulse

A group of damping ratios ζ is selected as $\zeta = 0.005, 0.010, 0.020, 0.030, 0.040, 0.050, 0.060, 0.070$. The response spectrum of the pressure wave (Fig. 3(a)) is illustrated in Fig. 5, indicating the following:

(1) The response spectrum of the pressure wave is complex, but show similarity in overall trend with the phase step shock spectrum. The low-frequency part of the spectrum is similar to the rectangle impact spectrum.

(2) When $\zeta > 0.030$, the response frequency spectrum is stable with its the middle and high frequency components eliminated.

where k is vibration system stiffness, ζ is damping ratio, ω_n is natural angular frequency, and ψ is phase.

The maximum value of x is derived (displacement shock spectrum) by differential Eq. (5):

$$\left(\frac{k}{F_0} x \right)_{\max} = 1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\pi \zeta / \sqrt{1-\zeta^2}} \times \cos \left(\pi - \tan^{-1} \frac{\zeta}{\sqrt{1-\zeta^2}} \right) = 1 + e^{-\pi \zeta / \sqrt{1-\zeta^2}}. \quad (6)$$

For a linear time-invariant system, the response of the general impulse $f(t)$ can be treated as the superposition of unit response function $h(t)$ at different moments [14]:

$$x(t) = f(t) * h(t). \quad (7)$$

The vibration of high-speed train body is generally measured by acceleration sensors. The acceleration response spectrum is calculated by [15]:

(3) When $\zeta > 0.030$, the response spectrum energy is concentrated under 35Hz;

(4) At the frequency bands below 15 Hz, the response spectrum fluctuates violently with multiple peaks.

4.3. Transient response of car body

The pressure wave discussed above is a transient response of linear single DOF. For a complicated car structure, it can be treated as a linear multi DOF system with small damping or a distribute system. Using canonical coordinates and canonical modes, the transient response of car body structure can be expressed by superposition of basic vibrations of many single DOF systems.

Fig. 5 The response spectrum of tunnel pressure wave

If n points are selected on the car body that is considered as a linear discrete system of n degrees of freedom system, n response functions can be expressed as a group of orthogonal polynomials:

$$S_{ai} = \frac{\sum_{k=0}^{2N-1} \alpha_{ik} p_k(\omega)}{\sum_{k=0}^{2N-1} \beta_k q_{ik}(\omega)}, \quad (9)$$

$$i=1, 2, \dots, n, \quad k=0, 1, \dots, 2N-1,$$

where N is the order corresponding with the analyzed frequency, $p_k(\omega)$ and $q_{ik}(\omega)$ are orthogonal polynomials, α_{ik} is an undetermined coefficient bearing relationships with the mode of lateral vibration, β_k is a coefficient related to the modal frequency and the damping ratio, and $p_k(\omega)$ and β_k are irrelevant to point position. If the damping ratios of these points are the same, Eq. (9) will be a fundamental formula of calculating the wall body transient response. Reference [16] uses single mode response superposition to obtain the transient response of the body structure.

5. Conclusions

(1) When two trains pass each other, the pressure wave amplitude is 1.3–1.8 times larger than that in single train operation, and the pressure wave contains product wave instead of sole superimposed wave.

(2) The pressure wave during the meeting is a non-symmetrical pulse featured with a sharp front, large amplitude, fluctuating central section, and less sharp tail. The pulse width is inversely proportional to the train speed. As the speed increases, the impulse amplitude is amplified, and the speed of pulse front is advanced.

(3) The response spectrum of the car body is complex. The primary frequency band falls below 35 Hz, and the frequency band below 15 Hz is the focal point that needs to be considered in structural design.

(4) When $\zeta > 0.03$, the car body is more capable of resisting the impact of the pressure pulse, especially the middle and high frequency components.

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