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# Effects of vehicle speeds on the hydrodynamic pressure of pavement surface: Measurement with a designed device

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ABSTRACT

The hydraulic characteristics of pavement, such as pore water pressure, hydrodynamic pressure, and permeability, have a great influence on the functional performance and durability of pavement. The main objective of this study is to design a device for measuring the hydrodynamic pressure of pavement surface and analyze its characteristics with different vehicle speeds. In order to investigate the influence of vehicle speeds on the hydrodynamic pressure of pavement surface, a device equipped with five fiber Bragg grating (FBG) sensors was designed and utilized to measure the surface hydraulic characteristics at four vehicle speeds in the field. The calibration of FBG sensor was conducted by the interrogator (SmartScan Aero) under given pressures from 0 MPa to 1 MPa with an interval of 0.1 MPa. Then, the device was embedded in the pavement and compacted by an auto wheel, which traveled over the device at different speeds. Furthermore, the experimental data was collected by the interrogator during the process of a moving tire touching the surface of the device. The experimental results showed that the correlation coefficient between the given pressure and the center wavelength change of the FBG sensor was 0.99, which means the FBG sensor was accurate and reliable. The hydrodynamic pressure of the pavement surface increased with the increase in vehicle speed from 40 km/h to 100 km/h. Moreover, the directional anisotropy of the hydraulic pressure was found to be dependent on vehicle speed.


## 1. Introduction

Pavement bears the wheel loading subjected from vehicles and provides friction for tires to ensure vehicle movement. In the rainy days, the rain will fall directly on the pavement surface. A certain thickness of water film or layer would be formed due to long-term rain, which has adverse influence on the safety and durability of the pavement. The water film decreases the friction between the tire surface and the pavement surface [1]. It is a great threat to driving safety as braking efficiency and steering precision at high speeds would be weakened by the decrease in friction. The hydrodynamic behavior is produced when the moving tire exerts pressure on the water film. The hydrodynamic pressure leads to splashing and spraying, which has an effect on the visibility of driving and induces traffic accidents [2,3]. Moreover, the splash and spray caused by hydrodynamic pressure would produce noise, and the quality of life of the residents living around the road would be affected by the noise. In terms of asphalt pavement, the pore structure of pavement is filled with the invading water and the surface of pavement is covered with a layer of water on a rainy day. The pore hydraulic pressure would be produced when the surface hydraulic pressure infiltrates the pores under the effect of loading on the pavement surface. Gao et al. studied the pore hydraulic pressure in asphalt pavement and its effects on permeability, and found that the pore hydraulic pressure increased with increasing vehicle speed [4]. The decline in the adhesive ability between aggregates and asphalt binder result in stripping and raveling of the pavement surface when asphalt pavement was in saturated conditions for a long time [5,6]. One of the stripping mechanisms is crack propagation in thin asphalt film, and the morphological characteristic of aggregates affects the homogeneity of asphalt film [7]. Hydrodynamic pressure induces stripping. Additionally, the alternation between positive pressure and negative pressure and the anisotropy of hydrodynamic pressure at different orientations promoted the progress of stripping and raveling of asphalt mixture particles, and the durability of the pavement performance was also decreased [8]. Asphalt pavement would be deteriorated further to

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form distresses such as cracks, pits and subsidence under the effect of hydrodynamic pressure, especially in conditions of high vehicle speeds and heavy traffic loads.

At present, two methods were utilized to research hydrodynamic pressure. The one is the numerical simulation technology, such as finite element simulation. The permeability coefficient and the hydraulic characteristic of different types of pavement structures were analyzed by building a numerical model. The other one used to investigate the hydrodynamic pressure at the surface and the pores with different vehicle speeds was the experimental field test. Fwa et al. studied the effect of rib tires and pavement grooves on hydroplaning by means of three-dimensional finite element modeling [9–11]. Benedetto et al. built a model to simulate unsteady water flow in the pores of the mixture based on theoretical equations [12]. Kutay et al. investigated the dynamic fluid flow in asphalt pavement by means of building a model [13]. Xue et al. studied the effects of permeability, pavement modulus, and thickness on the pore water pressure of asphalt pavement [14].

However, most present studies on hydrodynamic pressure concentrated on the analysis of the vertical hydrodynamic pressure at different vehicle speeds or indifferent pavement structures. There was little attention paid to the anisotropy characteristic of the hydrodynamic pressure at different orientations. In fact, the anisotropy of surface hydrodynamic pressure has an effect on the orientation of moving water film [15]. Generally, the drifting phenomenon or drifting trend would be produced whilst steering a vehicle at high speeds. Vehicle handling would also become more challenging as the reacting force from the surface hydrodynamic pressure acts on the tire as the vehicle is steered. The speed was one of key factors affecting centrifugation and hydrodynamic behavior. Consequently, it is of great significance to study the effect of anisotropy involved in surface hydrodynamics at different speeds on the safety of driving on rainy days.

Generally, the types of Fiber Optic Sensors (FOS) include FBG sensors, interferometric FOS, fiber optic micro bend sensors, distributed sensors, polarimetric sensors and hybrid sensors [16]. According to the different periods of the refractive index modulation, fiber Bragg gratings (FBG) and Long Period Gratings (LPG) were the two considered representative gratings [17,18]. Due to its high efficiency, the FBG sensor has been the most widely used device among them to measure axial strain. In regards of this, the FBG sensor was utilized in this study to measure the hydrodynamic pressure of the pavement surface. Previous studies have stated that temperature has an influence on the characteristic of water and the sensitivity of the FBG sensor [19,20]. It is necessary to measure the hydrodynamic pressure of the pavement surface at a relatively constant temperature. In this study, five specific dimensional FBG sensors were fabricated, and a device that can measure the pressure with five orientations was designed. The experimental results include the hydrodynamic pressure, the change trend and the change rate of pressure, which can be used to analyze the characteristics of the hydrodynamic pressure of the pavement surface. The measured data of the surface hydrodynamic pressure provided accurate parameters for the analysis of numerical simulation, and further improved the precision of numerical simulation. This study laid out a certain foundation for researching the characteristics of hydrodynamic pressure of pavement surface further in the future.

## 2. Research objectives and scope

The main objective of this study is to design a device to measure the hydrodynamic pressure of the pavement surface and analyze its characteristics with different vehicle speeds. The FBG sensor employed in this study is an accurate and reliable instrument, which can measure a slight change in hydrodynamic pressure. The hydrodynamic pressure between the pavement surface and the moving tire has significantly complicated characteristics, negatively impacting the safety and durability of pavement. This research introduced the principle and calibration of the FBG sensor. A device equipped with five FBG sensors was selected to measure the hydrodynamic pressure of pavement surface in different orientations. The vehicle speeds ranged from 40 km/h to 100 km/h in line accordance with the pavement condition on rainy days and relevant legal provisions for motorways in China. The technological process of this research is shown in Fig. 1.

## 3. Mechanism and methodology

### 3.1. The Mechanism and calibration of the FBG sensor

As shown in Fig. 2, FBG is an optical device that uses a strong ultraviolet laser to burn grating on the center of the fiber and has the function to select a specific wavelength. The light with a specific wavelength would be reflected strongly when it transfers through FBG, while the remaining lights with other wavelengths could transfer through FBG without energy loss. This wavelength can be regarded as the characteristic wavelength of an FBG.

The main concept of the FBG sensor is that the characteristic wavelength of an FBG shifts when the stress within the FBG changes [21]. The stress can be back-calculated by detecting the shift in the central wavelength of the FBG. According to the couple-mode theory, the equation involved in the reflection wavelength ($\lambda_B$) of uniform FBG is as follows [22]:

$$\lambda_B = 2n_e\Lambda \tag{1}$$

where $n_e$ is the effective refractive index and $\Lambda$ is the period of grating.

From Eq. (1), it can be seen that the reflection wavelength of FBG is directly proportional to the effective refractive index and the period of FBG. In terms of non-uniform fiber, the period of FBG would be influenced by the shrinkage of the fiber due to temperature. The shift in wavelength of the FBG is determined by the following equation:

$$\Delta\lambda_B = \lambda_B(1 - \rho\alpha)\Delta\xi + \lambda_B(\alpha + \xi)\Delta T \tag{2}$$

where $\Delta\lambda_B$ stands for the wavelength shift of FBG, $\rho\alpha$ is the elastic-optic coefficient, $\alpha$ is the thermal expansion coefficient, $\xi$ is the calorescence coefficient, $\Delta\xi$ is the strain shift and $\Delta T$ is the temperature change.

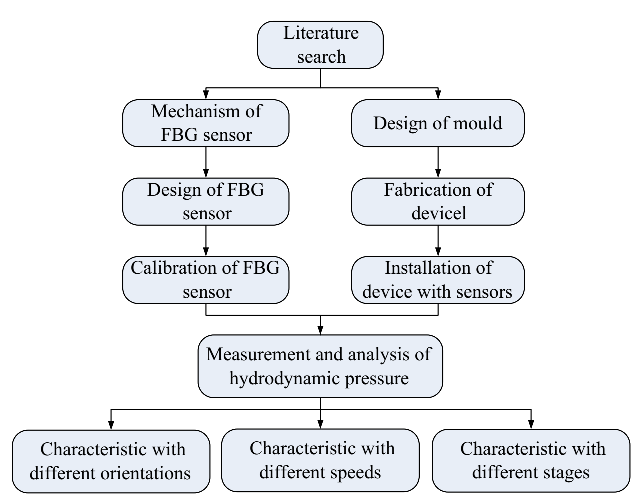


**Fig. 1.** The technological process.