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# EXPERIMENTAL STUDY OF AIR PUMPING IN A ROAD CAVITY

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## ABSTRACT

This article deals with the experimental identification of the aerodynamic phenomena leading to rolling noise and more precisely the air pumping mechanism accompanied by air resonances when a tyre passes over a road cavity. Dynamic air pressure measurements at the cavity bottom were carried out on a specific test rig. The latter is a reduced scale representation of a smooth tyre rolling on a cylindrical cavity of adjustable depth. Time pressure fluctuations were measured using piezoelectric sensors integrated in the cavity. These fluctuations can be broken down into three phases: a compression phase (during the gradual closing of the cavity), an overpressure phase with cavity resonance (during the total closure) and a release phase with pressure oscillations due to Helmholtz resonance (during the progressive opening). A parametric study was carried out by varying the rolling speed, the applied load and the cavity depth. In contrast to the applied load which only conditions the overpressure phase duration, the rolling speed and the cavity depth have a rather strong influence on air pressure fluctuations. Increasing the rolling speed and/or decreasing the cavity depth increased the overpressure generated at the cavity bottom as well as the pressure oscillations frequency during the release phase. The cavity depth had the greatest effect on the maximum pressure measured at the cavity bottom especially for the shallow cavities. This finding could be related to the tyre tread penetration into the cavity causing additional decrease in its volume resulting in stronger overpressure even more significant for shallower depths. It would therefore be interesting to measure this penetration by displacement sensors and use the result in a numerical model to highlight the impact of the cavity volume variation by comparing the measurements with the calculations.

## 1. INTRODUCTION

Air pumping is an aerodynamic source, which contributes to tyre/road noise. By this term are meant the series of rapid air compressions and expansions at the tyre/road interface. Several experimental studies have been carried out to study this phenomenon during the tyre rolling on the road. Two main cases were considered based on the presence of grooves or cavities on the tyre tread or on the road surface.

In the 1st case (tyre cavity), results [1, 2] characterize the pressure fluctuations and the air overpressures gener-

ated during air pumping as well as the air resonators excited as a result of this phenomenon. Others [3–5] highlight the influence of parameters related to the tyre on the attenuation or amplification of the air pumping. Some authors [6, 7] measured the generated acoustic pressure following various air compressions and expansions at the leading and trailing edges of the contact zone as well as the parameters influencing this sound pressure.

In the 2nd case, studies have been mainly based on a slick tyre rolling over a road cavity [8]. The dynamic air pressure was measured at the bottom of a cylindrical cavity with variable dimensions. The tyre passage causes an increase in the air pressure in the cavity generating an overpressure maintained during contact, then a pressure drop when the cavity opens followed by a Helmholtz resonance. Thus, the pressure signal has three main phases: compression, constant stage with closed cavity resonance and expansion with pressure oscillations.

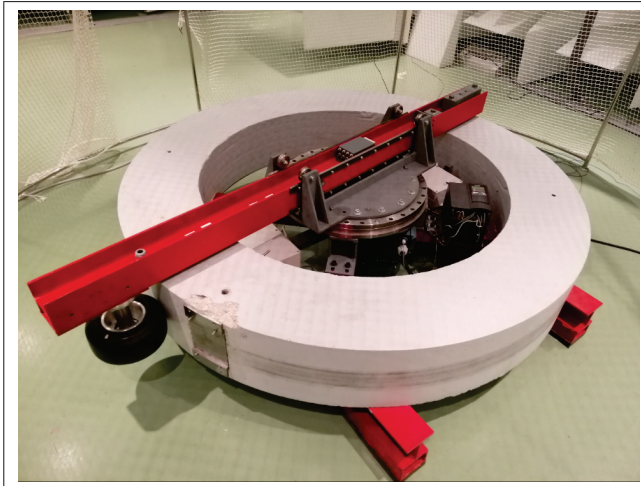
The aim of this paper is to experimentally improve the knowledge on the aerodynamic mechanisms leading to rolling noise in the case of a slick tyre passing over a road cavity. The dynamic air pressure measurements were carried out on the test rig for the tyre/road dynamic contact developed by Gustave Eiffel University (former IFSTTAR) in Nantes. This test rig was already used in [9] for the study of contact forces at the tyre/road interface. Here, air pumping mechanisms were studied at a reduced scale and in simplified configurations. A parametric study was carried out in order to analyze the influence of the applied load, the rolling speed and the cavity depth on the various aerodynamic phenomena generated at the tyre/road interface.

## 2. EXPERIMENTAL SETUP

### 2.1 Description Of The Equipment

The test rig consists in a concrete cylinder which outer vertical surface simulates a road surface on which a small tyre is rolling (Fig. 1). The tyre is a slick commercial kart tyre with a diameter of 252.4 mm. The concrete cylinder has an outside diameter of 2 m and is placed horizontally. This equipment makes it possible to control the speed and the load applied to the tyre and thus to study the phenomena under well-controlled experimental conditions.

Dynamic air pressure fluctuations at tyre/road interface are measured using a pressure piezoelectric sensor as shown in Fig. 2 (make PCB PIEZOTRONICS, model



**Figure 1.** Test rig used for the dynamic contact of the tyre with the road.

112A22). This serie of miniature pressure sensors is designed for high resolution applications and features acceleration compensation. Common use includes monitoring of high intensity sound and turbulence measurements, and many other industrial R&D applications.



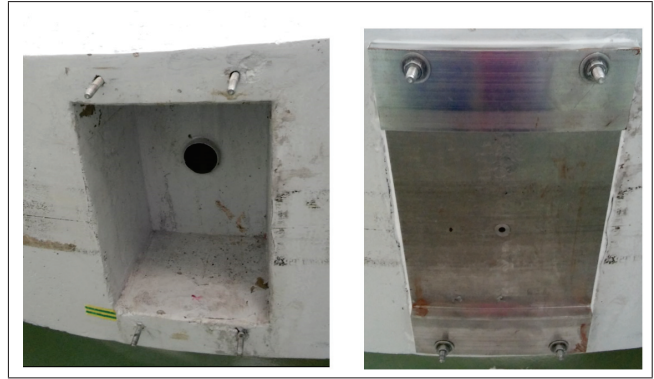
**Figure 2.** Pressure piezoelectric sensor of make PCB PIEZOTRONICS, model 112A22.

As shown in Fig. 3, a parallelepipedic volume was reserved on the outer surface of the test rig. This cavity enables to mount a metal plate having a width of 15 cm on which is placed the cavity incorporating the pressure sensor. This latter is actually screwed onto a support ring glued to the back of the metal plate (Fig. 4). The cavity has a diameter of 5 mm and a variable depth (1 mm, 5 mm, 10 mm, 20 mm and 30 mm), which can be adjusted by means of support rings of different dimensions.

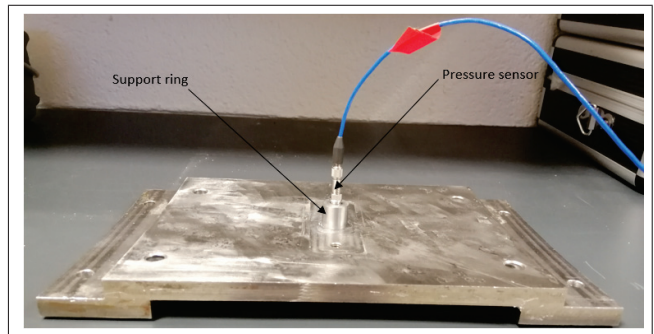
The pressure sensor is connected to a Brüel & Kjær data acquisition system that consists of a PULSE 3560-D type Brüel & Kjær front end and the Brüel & Kjær PULSE Labshop software v.14, which is used for data acquisition, storage and processing. Cables directly make the connection between the sensor set in the test rig and the acquisition system.

## 2.2 Experimental procedure

Before starting the pressure measurements, it is necessary to make sure that the temperature of the tyre is stable and therefore that stable rolling conditions are reached for each speed and load tested. Therefore, a series of tests were carried out by fixing first the applied load and then varying the rolling speed. Then, for each speed, the tyre temper-



**Figure 3.** Rectangular cavity (on the left) receiving the metal plate integrating the cylindrical cavity (on the right) on which the tyre is rolling.



**Figure 4.** The pressure sensor mounted on the metal plate.

ature was recorded at a given time interval until a stabilized temperature was reached (after around 20 minutes of rolling). This temperature thus varies between a minimum value between 27°C and 29°C, for a speed of 2.5 m/s and an applied load of 250 N, and a maximum value between 57°C and 63°C, for a speed of 15 m/s and an applied load of 1000 N. The obtained values are used as a reference for triggering the pressure measurements.

The test rig was placed in an air-conditioned room. Pressure measurements were carried out at an ambient air temperature of 20°C. Before starting each test, the tyre inflation pressure was adjusted to 1 bar. Then the tyre was rolled until the stable temperature corresponding to the load and speed has been reached. A given depth  $L$  was fixed. Then a given load  $P$  was fixed and the rolling speed  $v$  was varied. The depth was varied from [1; 5; 10; 20; 30] (mm); the load was varied from [250; 500; 750; 1000] (N) and the speed was varied from [2.5; 5; 7.5; 10; 12.5; 15] (m/s). Tab. 1 summarizes the test plan. The representativeness of the measurements for a configuration was ensured by averaging the measurements over several revolutions. For each test, 100 signals corresponding to 100 passages of the tyre over the cavity were recorded and saved. Then, the signals were exported and averaged, giving the resulting pressure at the bottom of the cavity for a given combination of cavity depth, rolling speed and load. The influence of each parameter is studied separately in the following, with regard to the compression and expansion phases.

L (mm)	v (m/s)	P (N)
1	[2.5; 5; 7.5; 10; 12.5; 15]	[250;500;750; 1000]
5	[2.5; 5; 10; 15]	[500;1000]
10	[2.5; 5; 7.5; 10; 12.5; 15]	[250;500;750; 1000]
20	[2.5; 5; 10; 15]	[500;1000]
30	[2.5; 5; 10; 15]	[500;1000]

**Table 1.** Parametric study plan of the tests.

### 3. RESULTS

#### 3.1 Signal Repeatability

Fig. 5 shows two examples, each of 100 measured pressure signals for two different speeds and for 100 tyre passages over the 30 mm deep cylindrical cavity. The resulting average signal is drawn in a thick yellow line for each case.

The repeatability of the 100 signals for each rolling condition is satisfactory. However, it is clearly seen that with the increase in speed, the signals become more and more influenced by the vibrations of the experimental device (Fig. 5b). Thus pressure oscillations are noticed, which are important more especially at the tyre arrival time on the plate (before the pressure increase phase) as well as at the time of its departure (after the pressure oscillation phase).

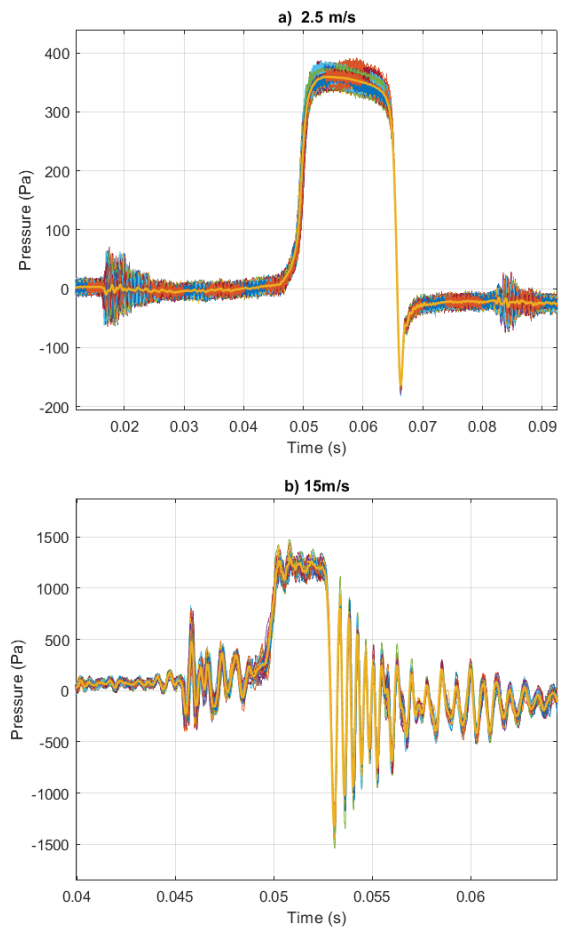
On the other hand, this repeatability is also satisfactory by comparing the 100 signals with the average signal, especially in the expansion phase. The deviation of the maximum pressure reached from the average maximum pressure was calculated for all the configurations tested and was found less than 3.5 % on average, which is considered as satisfactory for the purpose of the study.

#### 3.2 Signal Shape

Fig. 6 shows the general shape of the pressure signal obtained at the cavity bottom. This is consistent with the literature [8, 10].

Indeed, the signal can be decomposed into 3 main phases:

- the compression phase when the cavity is gradually closed: the pressure gradually increases until reaching a maximum value (overpressure at the bottom of the cavity) ;
- the overpressure phase when the cavity is completely closed by the tyre. This phase is characterized by a constant pressure stage.
- the expansion phase during the gradual opening of the cavity, represented by a pressure drop followed by damped oscillations characterizing the Helmholtz resonance. This phenomenon is caused by the resonance of the circulating air when the tyre surface detaches from the roadway due to the presence of cavities. The Helmholtz resonance can be compared



**Figure 5.** Pressure signals at the bottom of the cavity corresponding to 100 tyre passages over the 30 mm deep cavity, for a load of 1000 N and at a speed of a) 2.5 m/s b) 15 m/s. The thick yellow signal corresponds to the average signal.

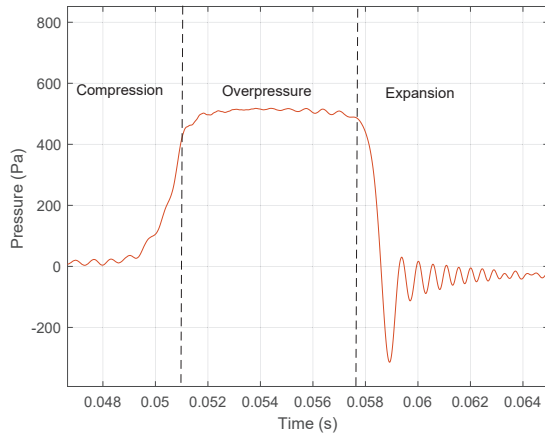
to that of a mass-spring vibratory system. The air confined in the dihedral (formed by the tyre/road geometry) at the trailing edge is considered to be the mass and the volume of the cavity is considered to be the spring. This phenomenon only occurs at the trailing edge of the tyre.

These pressure fluctuations constitute the phenomenon under study in the following by varying the cavity depth, the rolling speed and the applied load.

#### 3.3 Effect Of The Applied Load

Results generally show that the pressure measured at the cavity bottom is slightly influenced by the applied load, especially for cavities of great depth and at high speeds. This was valid for all the tested depths and speeds. An example on the pressure variation as a function of the load for the 10 mm deep cavity and the speed of 12.5 m/s is shown in Fig. 7. As it can be seen, the higher the load the higher the duration of the overpressure stage, due to the increase of length of the tyre/road contact area in the rolling direction.





**Figure 6.** Pressure signal measured at the bottom of the 5 mm diameter cavity ( $L = 30$  mm;  $P = 1000$  N,  $v = 5$  m/s).

However, the load does not affect the maximum pressure level reached in the compression phase (Fig. 7a) nor the frequency and amplitude of the pressure oscillations in the expansion phase (Fig. 7b).

Since the load proves to be a less important parameter compared to the cavity depth and the rolling speed, it will be fixed in the following and the results are only presented for a load of 1000N.

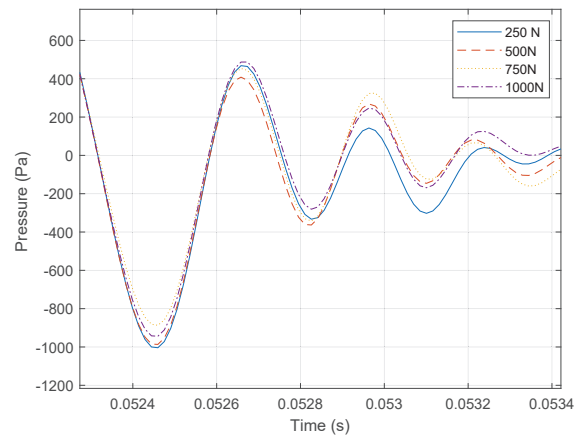
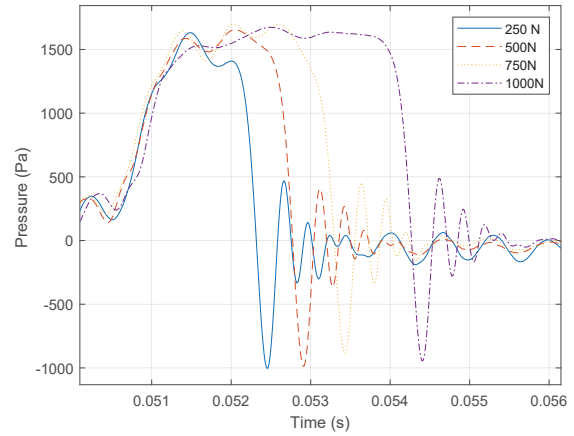
### 3.4 Effect Of The Rolling Speed

Fig. 8 shows the variation of the pressure signal measured at the bottom of the cavity due to the variation of the rolling speed, for a load of 1000 N and for two different depths (1 mm and 10 mm), plotted as a function of the traveled distance. The overpressure generated at the cavity bottom increases with the rolling speed. Moreover, the pressure difference between the maximum and the minimum reached pressures, generated at expansion phase when the cavity is fully open, increases with speed. Thus air pumping represented by these pressure fluctuations increases with increasing speed. The above results were valid for all the tested depths.

The variation of the average maximum pressure, calculated on the pressure stage phase, as a function of the rolling speed, is plotted in Fig. 9. Let  $r = L/D$  be the ratio between the cavity depth  $L$  and its diameter  $D$ . The relationship between the maximum pressure and the speed is linear for  $r \geq 4$  ( $L = 20$  mm and 30 mm). This relationship is all the more non-linear as  $r$  decreases ( $1 \text{ mm} \leq L \leq 10 \text{ mm}$ ).

On the other hand, the pressure stage during the compression phase tends to have a flatter shape as the speed decreases and includes oscillations with increasing speed. These oscillations are more remarkable with the increase in the cavity depth and are due to parasitic vibration of the experimental equipment.

However, the length of this stage and therefore the contact area slightly varies in general with the speed. This is shown in Fig. 10 where the contact area  $l_c$  is plotted



**Figure 7.** Variation of pressure depending on the applied load ( $L = 10$  mm;  $v = 12.5$  m/s) a) compression phase b) expansion phase.

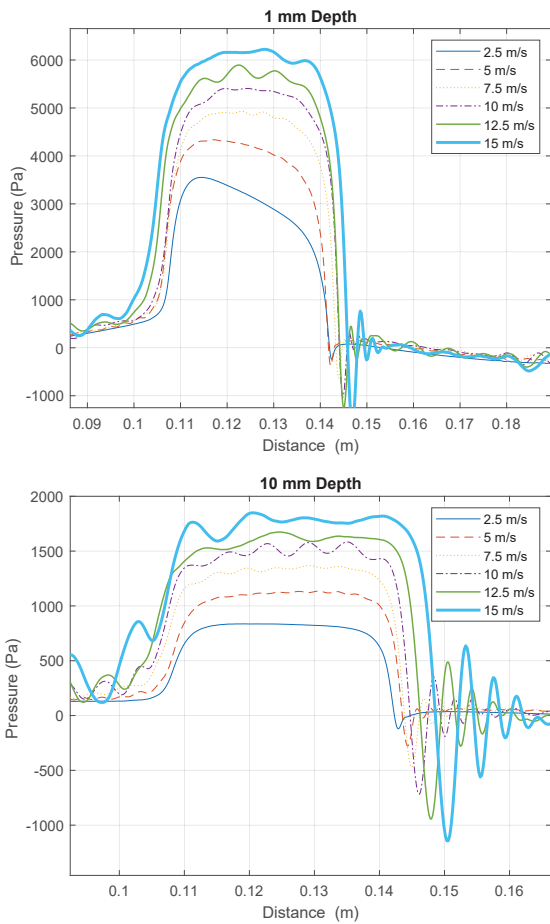
as a function of the rolling speed for the different tested depths. The contact can then be considered almost static with  $31 \text{ mm} \leq l_c \leq 40 \text{ mm}$ . This is consistent with the quasi-static nature of tyre/road contact observed with the same equipment in [11].

Concerning the expansion phase, and according to Fig. 11, if the speed increases, the amplitude and the frequency of the oscillations increase, but the number of oscillations decreases.

### 3.5 Effect Of The Cavity Depth

The variation of pressure measured at the cavity bottom is given in Fig. 12 for different cavity depths, at the speed of 10 m/s.

For all the tested speeds, the overpressure generated at the cavity bottom increases if the cavity depth decreases. This pressure increase is due, on the one hand, to the air trapping in an increasingly reduced volume as the depth of the cavity decreases, which increases the pressure inside of the cavity for the same applied load. This result was found in [12] which simulates the passage of a slick tyre at full scale over a cylindrical cavity without volume variation. On the other hand, the penetration of the tyre tread into the cavity during contact can magnify this increase of the

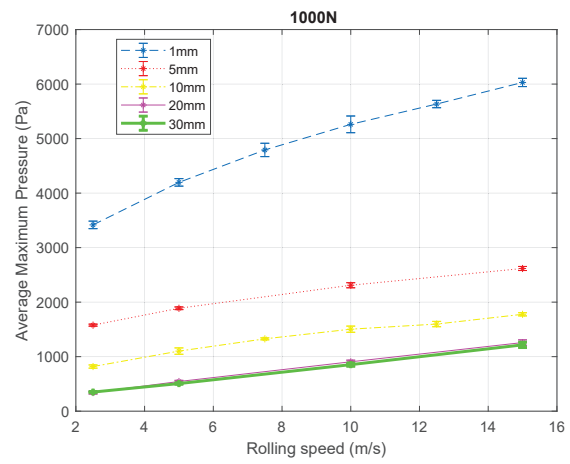


**Figure 8.** Variation of pressure for different rolling speeds ( $P = 1000$  N) during the compression phase as a function of the traveled distance.

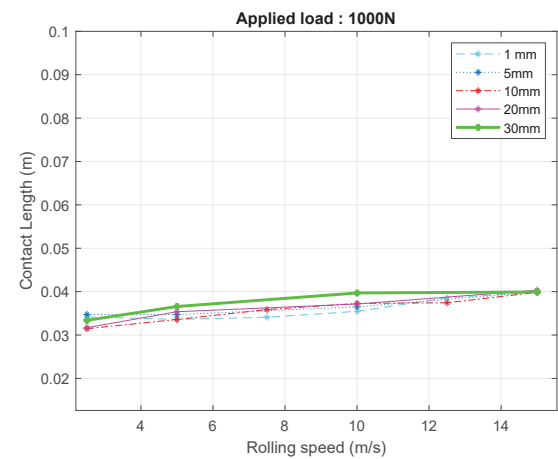
overpressure especially for small cavities. The penetration causes a change in the cavity volume, which proportionally has a greater impact for shallow depths. Thus, with the increase in depth, the variation in volume due to the penetration becomes negligible compared to the volume of the cavity. The volume variation was in fact numerically highlighted in [13] and [14], where the tread penetration was calculated and modeled by using different methods. In all cases, the change in volume increases the generated overpressure at the cavity bottom during contact with the tyre. Furthermore, by comparing the numerical results with experimental results dealing with the same configuration, the agreement is much more satisfactory when the variation in volume was taken into account [13].

On the other hand, from a given depth increase, the maximum pressure becomes invariant with respect to the depth. Besides, the difference between the maximum and the minimum pressures, generated at the opening of the cavity, decreases as the depth increases. Air pumping thus decreases with the increase of the cavity depth.

The pressure stage during the compression phase is more pronounced as the depth increases and its duration (therefore the contact area length) remains almost constant with the depth variation, which is also shown in Fig. 10.



**Figure 9.** Variation of the average maximum pressure as a function of the rolling speed for the different cavity depths ( $P = 1000$  N).



**Figure 10.** Variation of contact area length in the direction of rolling as a function of the rolling speed, for all the cavity depths ( $P = 1000$  N).

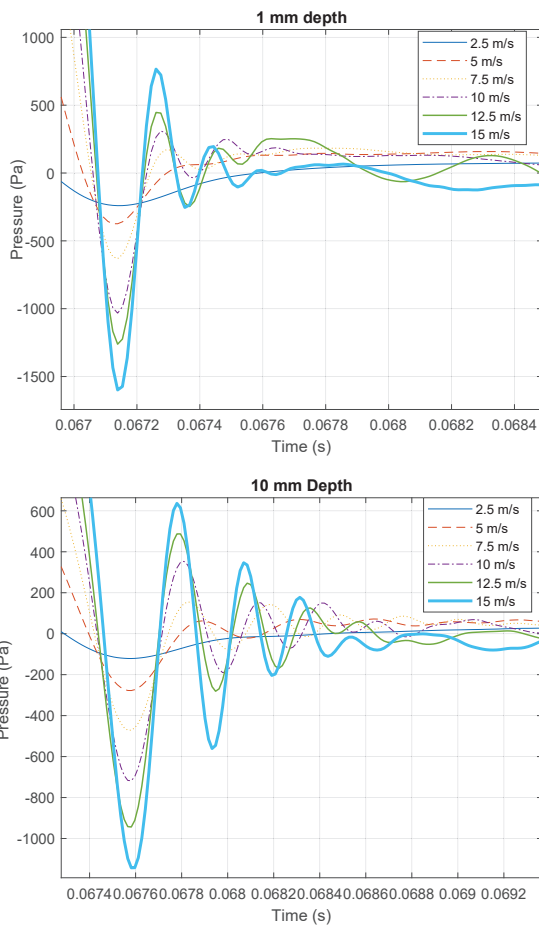
As for the expansion phase, and according to Fig. 13, if the depth of the cavity increases, the amplitude and the number of the oscillations increase, but their frequency decreases.

This result was expected since the Helmholtz resonator frequency is inversely proportional to the volume of the cavity according to the following equation [12]:

$$f = \sqrt{\frac{K}{m}} = \frac{1}{2\pi} \sqrt{\frac{\rho c^2 \frac{S_0^2}{V_c}}{\rho V_m}} = \frac{c}{2\pi} \sqrt{\frac{S_0^2}{V_m V_c}} \quad (1)$$

where  $K$  represents the stiffness and  $m$  the mass of the equivalent mass-spring system. The variables  $V_c$  and  $V_m$  respectively represent the cavity volume and the air mass volume in resonance.  $S_0$  is the area of the cavity opening (between the roadway and the tyre) and  $c$  is the speed of sound in the air.

The cavity depth is then a very important parameter which influences air pumping. By comparing the effects



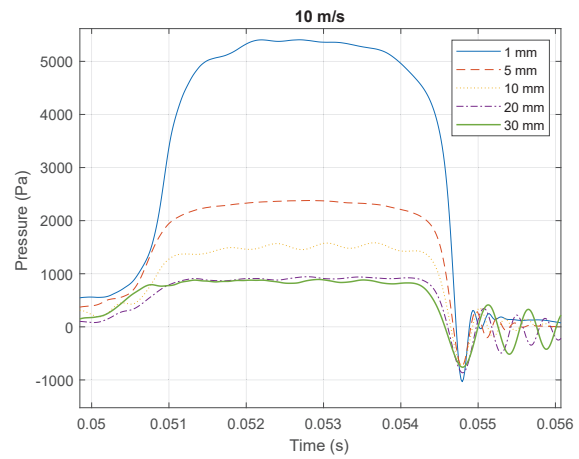
**Figure 11.** Variation of pressure for different rolling speeds ( $P = 1000$  N) during the expansion phase.

resulting from the various parameters above (subsections 3.3 to 3.5), it can be noticed that the impact of the cavity depth variation, and therefore the cavity volume variation, has the greatest effect on air pumping; which once again enhances the effect of the tread penetration during the passage of the tyre on the road cavity.

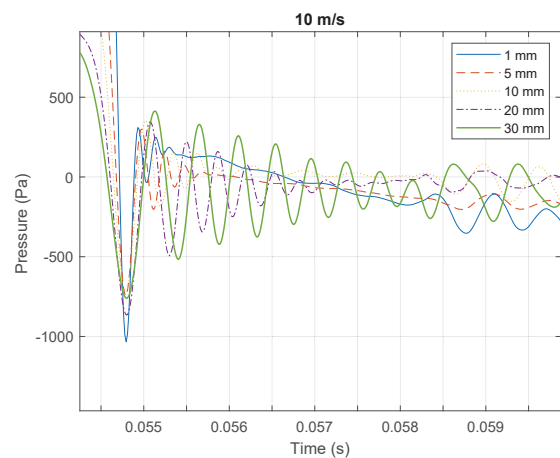
#### 4. CONCLUSIONS

This paper deals with the experimental study of air pumping on a specific test rig which simulates the rolling of a small tyre on a circular concrete base representing the road surface and comprising a cylindrical cavity with a diameter of 5 mm and a variable depth. The parametric study carried out consisted in varying the applied load, the rolling speed and the cavity depth. The dynamic air pressure measurement at the bottom of the cylindrical cavity made it possible to study the influence of these parameters on air pumping and therefore to improve knowledge of this phenomenon.

The dynamic air pressure signal at the cavity bottom following the passage of the tyre consists in 3 phases: compression during the gradual closing of the cavity, overpressure stage during the full closure of the cavity and expansion with pressure oscillations when the cavity opens.



**Figure 12.** Variation of pressure for different cavity depths ( $P = 1000$  N) during the compression phase.



**Figure 13.** Variation of pressure for different cavity depths ( $P = 1000$  N) during the expansion phase.

Apart from the variation of the contact length, the effect of the load on the pressure at the cavity bottom is negligible. On the contrary, increasing the rolling speed or decreasing the cavity depth, increases the pressure at the cavity bottom. The contact was found to be almost static since the contact length, represented by the pressure stage length, slightly changed with the speed variation.

As for the expansion phase, an increase in speed increases the frequency and the amplitude of the oscillations but decreases their number. However, an increase in the cavity depth decreases the frequency of the oscillations but increases their amplitude and their number.

In addition, the variation in the cavity depth and therefore its volume had the greatest impact on the pressure fluctuations at the cavity bottom during the passage of the tyre. This is very likely to be related to the penetration of the tread during contact causing the variation in the volume of the air cavities at the tyre/pavement interface generating additional overpressures, especially for cavities at shallow depths.

It would therefore be interesting to simulate the varia-

tion in the cavity volume through a numerical model similar to [13] and [14], and carry out comparisons with measurements in order to highlight the effect of the tread penetration on the air pressure at the cavity bottom. The cavity volume variation could be directly measured on the test rig using specialized displacement sensors and determining the tread penetration inside of the cavity.

## 5. ACKNOWLEDGEMENTS

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## 6. REFERENCES

- [1] K. J. Plotkin, M. M. Montroll, W. R. Fuller, and H. J. Nozick, "Identification of Tire Noise Generation Mechanisms Using a Roadwheel Facility," in *Proc. of the International TireNoise Conference*, (Stockholm, Sweden), pp. 127–141, 1979.
- [2] K. Schaaf, D. Ronneberger, and P. Neuwald, "Noise of a rolling tire - Flow and pressure variations in the region of the contact patch," in *Proc. of the INTROC 90 - International Tire/Road Noise Conference 1990*, (Gothenburg, Sweden), pp. 9–17, 1990.
- [3] P. R. Donovan and L. J. Oswald, "Quantification of noise mechanisms of blank, rib, and cross-bar tread bias-ply truck tires," Tech. Rep. GMR-3750, General Motors Research Laboratories, Warren, MI, Jul. 1981.
- [4] J. Ejsmont, U. Sandberg, and S. Taryma, "Influence of Tread Pattern on Tire/Road Noise," SAE Tech. Paper 841238, SAE International, Warrendale, PA, Sept. 1984.
- [5] K. Iwao and I. Yamazaki, "A study on the mechanism of tire/road noise," *JSAE Review*, vol. 17, pp. 139–144, Apr. 1996.
- [6] M. Jennewein and M. Bergmann, "Investigations Concerning Tyre/Road Noise Sources and Possibilities of Noise Reduction," *Proc. of the Institution of Mechanical Engineers, Part D: Transport Engineering*, vol. 199, pp. 199–206, July 1985.
- [7] J. Eisenblaetter, *Experimental investigation of air related tyre/road noise mechanisms*. PhD Thesis, Loughborough University, Loughborough, England, 2008.
- [8] J.-F. Hamet, C. Deffayet, and M.-A. Pallas, "Air-pumping phenomena in road cavities," in *Proc. of the INTROC 90 - International Tire/Road Noise Conference 1990*, (Gothenburg, Sweden), pp. 29–35, 1990.
- [9] Y.-F. Zhang, *Study on a test rig of dynamic tyre/road contact forces at the origin of rolling noise*. PhD thesis, Ecole Centrale de Nantes ; Université Bretagne Loire, Oct. 2016.
- [10] F. Conte and P. Jean, "CFD modelling of air compression and release in road cavities during tyre/road interaction," in *Proc. of the Euronoise 2006*, (Tampere, Finland), 2006.
- [11] Y.-F. Zhang, J. Cesbron, H.-P. Yin, and M. Bérengier, "Experimental Study of Normal Contact Force Between a Rolling Pneumatic Tyre and a Single Asperity," *International Journal of Applied Mechanics*, vol. 09, Article 1750081, Sept. 2017.
- [12] F. Conte, *Modélisation CFD du phénomène acoustique de pompage d'air dans un contact pneumatique/chaussée*. PhD Thesis, INSA Lyon, Lyon, France, Jan. 2008.
- [13] M. Bou Leba Bassil, J. Cesbron, and P. Klein, "CFD modeling of pressure variation in a road cavity with volume variation," in *23rd International Congress on Acoustics*, (Aachen, Germany), pp. 506–513, EEA, ICA, DEGA, Sept. 2019.
- [14] M. B. L. Bassil, J. Cesbron, and P. Klein, "Tyre/road noise: A piston approach for CFD modeling of air volume variation in a cylindrical road cavity," *Journal of Sound and Vibration*, vol. 469, Article 115140, Mar. 2020.