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INFLUENCE OF THE INTAKE VALVES PHASE SHIFT ON THE ENGINE INTAKE AIR MASS FLOW RATE

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Abstract. *The intake valves of an internal combustion engine were phase shifted with the objective to increase the intake air mass flow rate. Experiments were conducted in the cylinder head of a production 1.0-liter engine, with two intake valves per cylinder and only one working cylinder. The flow conditions of the engine intake system were reproduced in a Flow Bench. Pressure and mass flow rate variations with intake valves phase shift were obtained, considering the fluid dynamics characteristics of the intake flow. A phase shift angle that maximizes the mass flow rate was determined.*

Keywords *Engines, Pressure, Intake Valves, Flow Bench*

1. Introduction

Many solutions are proposed to improve the performance of spark ignition engines, such as utilization of turbochargers, superchargers, direct fuel injection systems and multi-valve systems. Fine tuning of the fuel injection system, the ignition system and the valve opening timing helps to increase the engine power (Cunha et al, 2000). Only a few production vehicle models present variable valve timing solutions. Such systems are often expensive, and cannot be used in the most popular models. Thus, the objective of this work is to investigate the existence of an optimum intake valves phase shift angle to increase the volumetric efficiency in multi-valve engines. This valve timing optimization system would be an inexpensive solution to be applied in popular models. The experimental investigation was carried out in a flow bench apparatus. The intake air mass and the pressure wave in the intake conduit were analyzed for a range of camshaft rotational speed and a variety of phase shift angles.

2. Literature Review

Dresner and Barkan (1989) proposed a mechanical valve actuator to allow for variable valve timing. With the same purpose, Urata et al (1993), Lenz et al (1989) and Cunha et al (2000) presented hydraulic valve actuators. Hara et al (1989) presented a hydraulic valve actuator to control the valve opening by the variation of the camshaft rotational speed. Pierik e Burkhard (2000) described a mechanical valve actuator with valve lift variation, evaluating the durability of the mechanism and its influence on fuel consumption, exhaust emissions, torque and combustion characteristics.

Morse et al (1938) showed the influence of the intake valves reciprocating movement on the pressure waves in the intake pipe. The authors realized that the pressure waves could be used to increase the engine volumetric efficiency. Benajes et al (1997) verified that the reflected pressure waves superpose the incident pressure waves. Winterbone (1999, 2000) showed that utilization of a Helmholtz resonator influenced the pressure distribution in the intake pipe at the moment the intake valve closes. Hanriot (2001) found that the shape of the pressure waves in the intake pipe is affected by the intake valve opening. Söderberg and Johansson (1997) studied the effects of intake valve opening variation on the intake air mass and engine volumetric efficiency.

3. Experimental Apparatus

The experiments were carried out in a flow bench (Fig. 1), equipment that allows for reproduction of conditions in the intake and exhaust systems of internal combustion engines. The valve movement was obtained through an electric motor coupled to the camshaft through a belt. The test section was connected to a plenum chamber, used to attenuate the pressure waves coming from the intake system. A fixed depression between the atmosphere and the plenum chamber is produced by a blower.

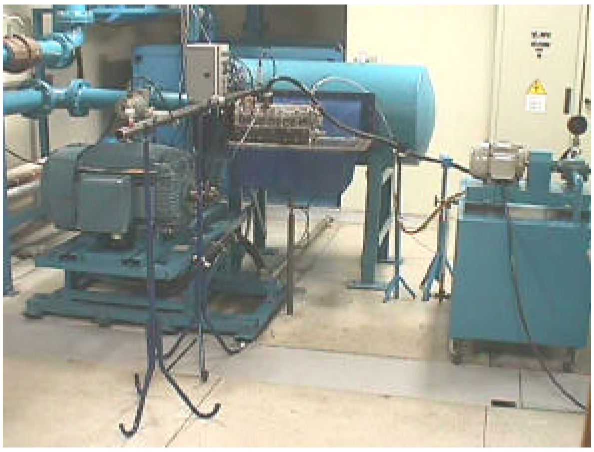

Figure 1. Flow bench.

For test execution the cylinder head of a production 1.0-liter, four-cylinder engine was used. The engine featured 70.0 mm bore, 64.9 mm stroke, two intake and two exhaust valves per cylinder. The cylinder head was divided into two parts; the lower part containing the combustion chamber, the intake and exhaust valves and manifolds, and the upper part containing the intake and exhaust camshafts. In the firing engine the exhaust camshaft was actuated by a belt linked to the crankshaft, while the intake camshaft was linked to the exhaust camshaft through a pair of gears.

To perform the experiments the upper part of the cylinder head was altered to phase shift the intake valves opening. The intake camshaft was cut between the cams of the first cylinder and an axle was inserted into the camshaft to allow for a relative movement between the cams. The upper part of the cylinder head was modified to allow a passage for the intake camshaft. A second pair of gears similar to that of the back of the cylinder head was mounted in the ends of the camshafts. A count gear of fifty-eight teeth was used as a reference for the camshaft position.

4. Experimental Methodology

The experiments were carried out for two intake conduit lengths, of 1.0 and 2.0 m. Analysis of intake air mass flow rate and pressure variation was made with only one operating cylinder. The tests were performed in the camshaft speed range from 200 to 2600 rev/min, in steps of 200 rev/min. Pressure measurements were made with piezoresistive pressure transducers, with operating range from –1 to 2 bar. For the 1.0 m length conduit three pressure transducers were employed, while, for the pipe of 2.0 m length, four transducers were located next to the intake port and along the conduit (Fig. (2)). Transducer P1 was located at 0.115 m from the valve port, P2 at 0.415 m, P3 at 0.985 m and P4 at 1.985 m. The ambient and the plenum chamber temperatures were monitored through platinum resistance sensors, with operating range from 0 to 68 ºC. To avoid overheating, the cylinder head was connected to a cooling system constituted by an oil reservoir and oil pump. The uncertainties of the measurements were ± 0,35 % of the upscale for pressure in the intake system and plenum chamber, ± 0,38 % for the ambient pressure, ± 0,5 % for temperatures, and ± 0,36 % for the intake air mass flow rate. The phase shift angles tested are shown in Tab. (1).

Table 1. Valve timings.

DESCRIPTION	NO PHASE SHIFT	PHASE SHIFT 10°	PHASE SHIFT 20°	PHASE SHIFT 30°	PHASE SHIFT 40°
First intake valve opens	TDC	TDC	TDC	TDC	TDC
Second intake valve opens	TDC	10°ATDC	20°ATDC	30°ATDC	40°ATDC
First intake valve closes	205°ATDC	205°ATDC	205°ATDC	205°ATDC	205°ATDC
Second intake valve closes	205°ATDC	215°ATDC	225°ATDC	235°ATDC	245°ATDC
Exhaust valves open	205°BTDC	205°BTDC	205°BTDC	205°BTDC	205°BTDC
Exhaust valves close	TDC	TDC	TDC	TDC	TDC

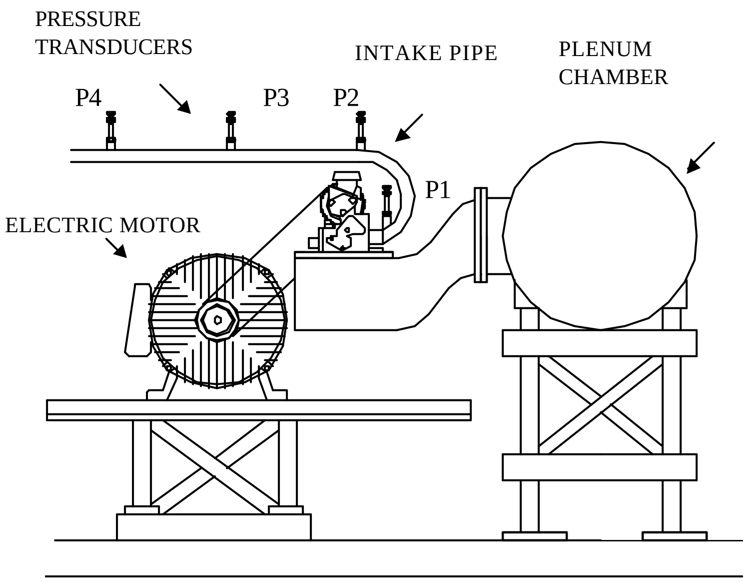

Figure 2. Schematics of the test section.

The camshaft speed range investigated corresponds to rotation frequencies between 3.33 and 43.33 Hz. Low displacement engines require higher torque at low speeds and, thus, it is desirable that the resonation speed of such engines happen for crankshaft speeds between 2500 and 3000 rev/min, which corresponds to camshaft rotation frequencies from 20.83 to 25 Hz.

Taking the intake conduit as a straight pipe with one harmonically vibrating valve in one end and open in the other end, the resonation frequency is given by (Kinsler, 1980; Hall, 1987):

$$f_n = \frac{n}{2}\frac{c}{L + \frac{8}{3\pi}a} \tag{1}$$

where L is the pipe length, c is the sound speed, n is the number of harmonics and a is the pipe ratio.

For a pipe with one harmonically vibrating valve in one end and the other end closed, the resonation frequency is given by (Kinsler, 1980; Hall, 1987):

$$f_n = \frac{2n-1}{4}\frac{c}{L} \tag{2}$$

Considering c= 330 m/s and a= 15,5 mm, Tab. (2) and Table (3) show values for several resonation frequencies for the two intake pipe length tested, for conduits with open ends and closed ends, respectively.

Table 2 – Resonation frequencies for conduits with open ends.

L (m)	FREQUENCY (Hz)				
	$f_{fundamental}$	$f_{1^o\ harmonics}$	$f_{2^o\ harmonics}$	$f_{3^o\ harmonics}$	$f_{4^o\ harmonics}$
1,0	162,25	324,49	486,74	648,98	811,23
2,0	81,81	163,61	245,42	327,22	409,03

Table 3 – Resonation frequencies for conduits with closed ends.

L (m)	FREQUENCY (Hz)				
	$f_{fundamental}$	$f_{1^o\ harmonics}$	$f_{2^o\ harmonics}$	$f_{3^o\ harmonics}$	$f_{4^o\ harmonics}$
1,0	82,50	247,50	412,50	577,50	742,50
2,0	41,25	123,75	206,25	288,75	371,25

5. Results

Figures (3) and (4) show the influence of the intake valves phase shift on the engine intake air mass flow rate, the results being the average of three tests performed for each configuration. It can be observed that the general behavior of the curves is similar for pipe lengths. The camshaft rotational speeds of 1200 and 2400 rev/min are critical conditions. At 2400 rev/min there is resonance of the intake pipe length of 2.0 m. At 1200 rev/min, which corresponds to the crankshaft rotational speed of 2400 rev/min, there is unstable engine operation.

Figure (5) presents the average mass flow rate in the speed range tested for all phase shift angles and both intake pipe lengths. An increase on the mass flow rate is observed up to the shift angle of 30 camshaft degrees, following by a decrease. A plausible explanation for that can rely on the pressure wave in the intake port by the time the intake valve opens.

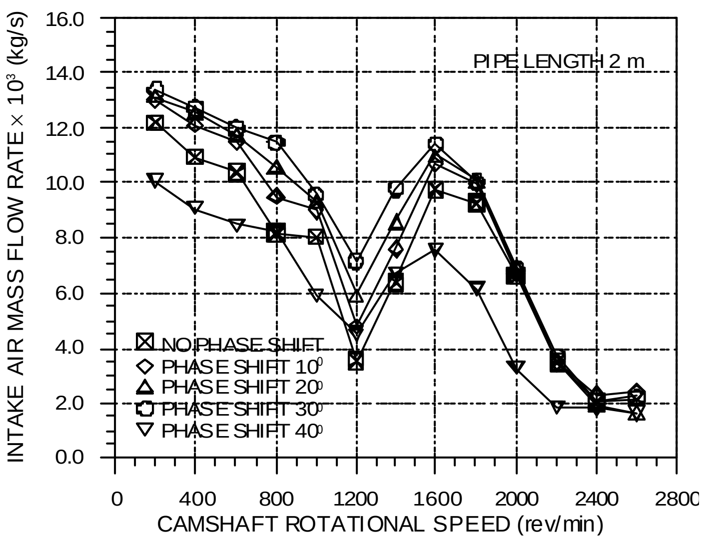

Figure 3 – Variation of the intake air mass flow rate with intake valves phase shift and camshaft rotational speed for the intake pipe length of 2.0 m.

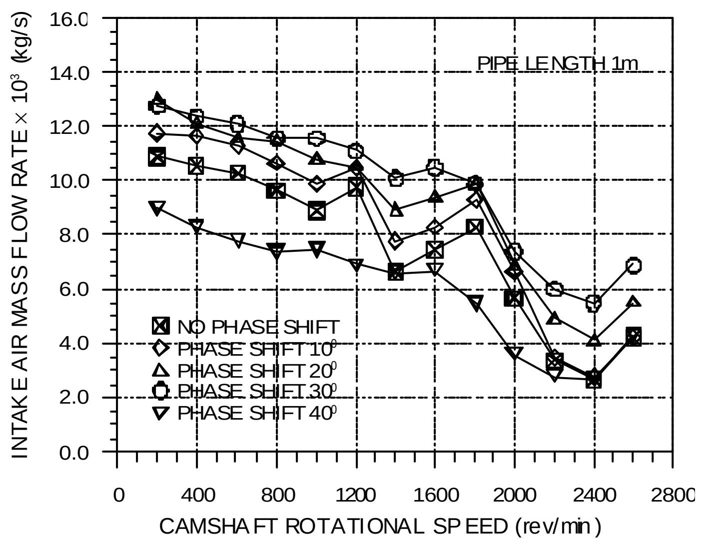

Figure 4 – Variation of the intake air mass flow rate with intake valves phase shift and camshaft rotational speed for the intake pipe length of 1.0 m.

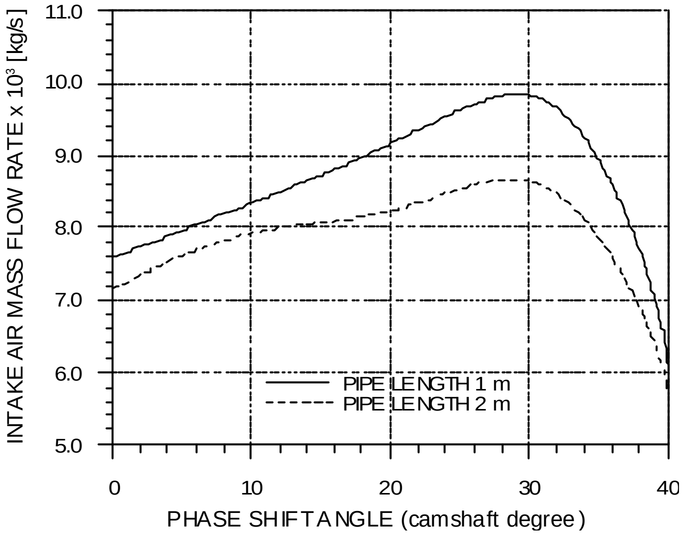

Figure 5 – Variation of the average mass flow rate in the speed range tested with intake valve phase shift angles for the intake conduits of 1.0 m and 2.0 m.

The results obtained for the mass flow rate should be analyzed considering that the intake pipe has a vibration mode of a wave quarter (Sassi, 1996). Using Eq. (2) for the conduit of 2.0 m length, Tab. (3) shows the the time spent by the wave to produce ten reflections and the reflected wave type in both pipe ends.

Table 3 – Analysis of the pressure signal in the intake port.

Number of wave reflections	1	2	3	4	5	6	7	8	9	10
Pressure signal in the valve port	+	-	-	+	+	-	-	+	-	-
Wave time (ms)	5,88	11,77	17,65	23,53	29,41	35,29	41,18	47,06	52,94	58,82

It can be observed that at low camshaft speeds the intake valve remains closed for a relatively long period, with a vibration mode of a wave quarter. In this situation, the wave has enough time to experience many reflections and considerable attenuation. Thus, for low speeds the pressure wave effects on the mass flow rate are not important. It should be noticed that the mass flow rate depends on the pressure wave behavior from the intake valve opening time until its closing time (Hanriot, 2001).

Figures (6) and (7) show the pressure waves along the intake conduit for a complete revolution of the camshaft. The mass flow rate is related to the difference between the pressure wave in the intake port and the constant pressure in the plenum chamber.

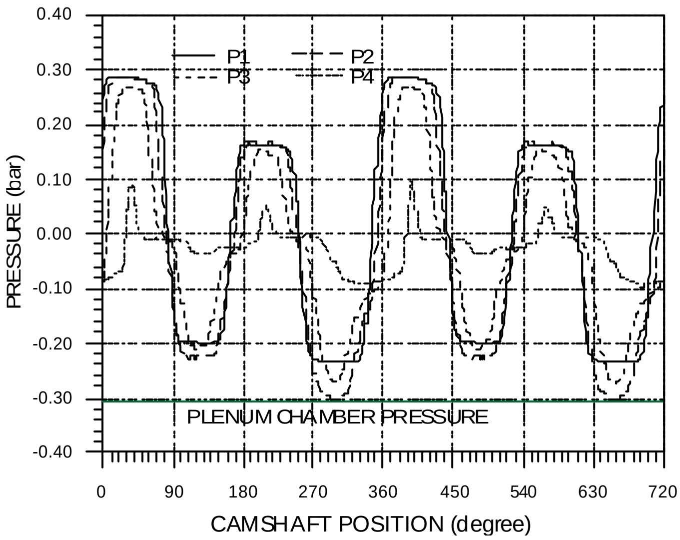

Figure 6 – Pressure along the intake conduit during an engine cycle at the camshaft speed of 1200 rev/min without intake valves phase shift.

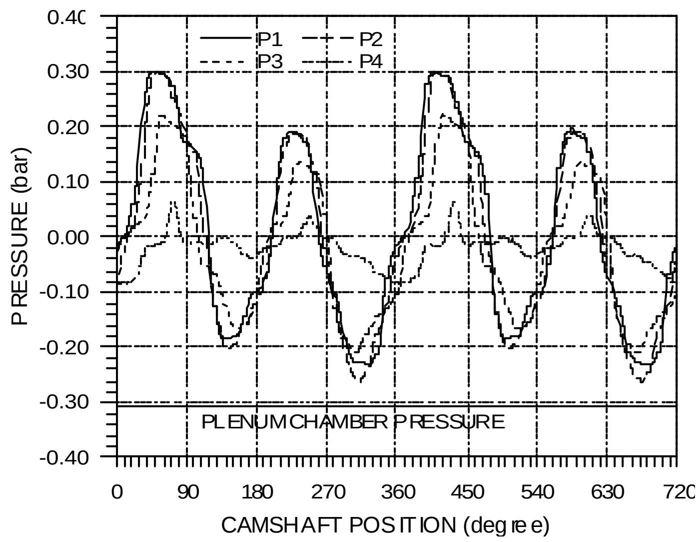

Figure 7 – Pressure along the intake conduit during an engine cycle at the camshaft speed of 1200 rev/min and intake valves phase shift angle 40 camshaft degrees.

6. Conclusions

- The general trends observed for the intake air mass flow rate were not significantly affected by the intake valves phase shift angle for a same intake pipe length in the speed range investigated.
- The trends presented for the intake air mass flow rate are related to the pressure wave resonance in the intake conduit.
- The intake air mass flow rate is affected by the intake pipe length.
- The effects of intake valves phase shift can be demonstrated through the pressure waves in the valve ports.
- The intake valves phase shift produces a damping effect in the pressure waves generated.
- At the phase shift angle of 30 camshaft degrees the highest mass flow rate was observed for the speed range and intake pipe lengths tested.

7. Acknowledgement

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