Performance of Provoked Ignition Engine for the Prediction of Exhaust Manifold Using a 1D Methodology and Experimental Test

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***Abstract*—The increase in power is a primary need in the preparation of a competition vehicle. In the present investigation, the exhaust manifold was optimized through the dimensions and configuration for a Suzuki Twin Cam vehicle with a G13B engine. A one-dimensional engine model was applied in the OpenWAM software, modifying the configuration of the exhaust manifold and the lengths to increase the performance with respect to the original system; the design of the most optimal manifold according to the simulations was built using two methods, bending (type A) and step header (type B), which was verified in the experimental test on a roller dynamometer to obtain the characteristic curves of the motor. The results, with respect to the original system, show a power increase of 8.41% and 10.33%, according to type A and type B construction, respectively; as well as an increase in torque of 3.26% for type A and 8.83% for type B. The results of the characteristic curves of the 1D simulation motor show a difference less than 9% with respect to the experimental tests, ensuring the computational process**

***Index Terms*—exhaust manifold, vehicle, OpenWAM, engine performance, design, dinamometer**

I. INTRODUCTION

In the last decades, the legislation on internal combustion engines (ICEs) has severely reduced the limits for pollutant and noise emissions. These requirements have established the research activity at design phase as a key stage in the engine production process [1-2]. Therefore, an intensive investigation on ICEs has carried out, focusing on the optimization of performances and fuel consumption [3-4]. The improvement of the flow conditions by trial and error of a prototype in the flow bank requires a lot of time and is very expensive. Even the manufacture of an exhaust manifold is a complex technique that as any process requires a regulation to follow. JIS G 4304 is the rule that governs the manufacture of this engine element since it handles the manufacture of tension-free steel strips according to Park et al. [5-6]. An important effort has been done seeking the improvement of the combustion and gas exchange processes, using tools such as OpenWAM is an open-source one-dimensional gas dynamic model able to calculate the air and gas flows within the intake and exhaust systems of internal combustion engines [7-8].

A primary need when preparing a competition vehicle is increasing the power, this carried out by reducing losses on friction, pumping or auxiliary systems [9]. The pumping losses have their origin in the replacement of the gases burned with fresh gases during the filling of the cylinder, which determines the volumetric efficiency, a relevant factor in the performance of the engine [10]. The exhaust ducts design adapted to the distribution diagram helps reduce pumping losses, improving the volumetric efficiency of an engine by 5% [7].

The propagation speed of pressure waves can be improved by a proper design of the manifold geometry [11]. As well as, modifying the exhaust length will benefit the energy from the flow oscillations, increasing the intake and therefore the torque of an engine [12], making it necessary to evaluate the configuration of the

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manifold 4-1 or 4-2-1, linked to the dimensions, to improve the performance of the engine [13].

A 4-1 configuration manifold helps to reduce turbulence, reduce flow losses, and theoretically has the highest flow rate so it works best at high revolutions [3]. Pulse exhaust manifolds, with a 4-2-1 configuration, generate a directional flow effect, which allows the increase of kinetic energy of the flow and avoids interference between the exhaust pressure pulses due to the order of ignition in the cylinders [14], e.g., Masi, Toffolo and Antonello [15] used the multiple 4-2-1 configuration on a modified Kawasaki ZX6R-07 motorcycle, increasing output power by 33% and torque by 16%.

Nowadays, 1D engine modeling allows evaluating various design options; predicting engine performance; identifying process control variables and making effective use of exhaust pressure waves to maximize volumetric efficiency; and the motor torque. Thus, with the help of computational computation using mathematical models, such as the Open WAM free code (a gas-dynamic tool 1D) a design can validated as shown on experimental tests [16]. The aim of the study is to develop a through the implementation of a 1D model of the engine for possible to evaluate the impact on the performance of the engine by modifying the parameters of the exhaust system with the respective validation of results on a dynamometric benchmark.

II. METHODOLOGY

The propose was behavior of two types of exhaust manifold configurations, 4-1 and 4-2-1, was verified, varying the length of the ducts in the engine rotation regime of 2 500 to 7 500 rpm, with the aid of the 1D simulation and after applicate the dynamometric tests [17].

A. Vehicle

Suzuki car with a twin cam engine used. The car had: an in-line four-cylinder engine; four valves per cylinder; with pistons, connecting rods and crankshaft standard; and 140 000 km. The engine characteristics and modifications are shown in Table I.

TABLE I. SPECIFICATIONS ENGINE G13B

Parameters	**Values**
Engine	G13B, DOHC
Total volume	1298 cm3
Diameter x stroke	74 × 75.5 mm
Compression ratio	10:1
Programmable ECU	Haltech Sprint 500
Ignition system	Independent coils
Order of ignition	1-3-4-2
Fuel system	MPF-i
Gas	Gasoline
Idle speed	850 ±50 rpm
Engine working temperature	80 ℃
Intake manifold	Suzuki Cultus
Air filter	K&N high flow
Cylinder head	Polished
Intake duct diameter	44 mm
Exhaust duct diameter	35 mm
Intake valve diameter	29.1 mm
Inlet valve opening	8 ºaTDC
Inlet valve closing	36 ºbBDC
Exhaust valve diameter	24.9 mm
Exhaust valve opening	42 ºaBDC
Exhaust valve closing	10 ºbTDC

B. 1D Simulation

The simulation achieved on the Open WAM software, in which the engine and intake system were modeled and kept constant [8]; the exhaust system modified according to the two manifold configurations. In the 4-1 configuration the exhaust ducts of the four cylinders are joined in a single manifold, as shown in Fig. 1.

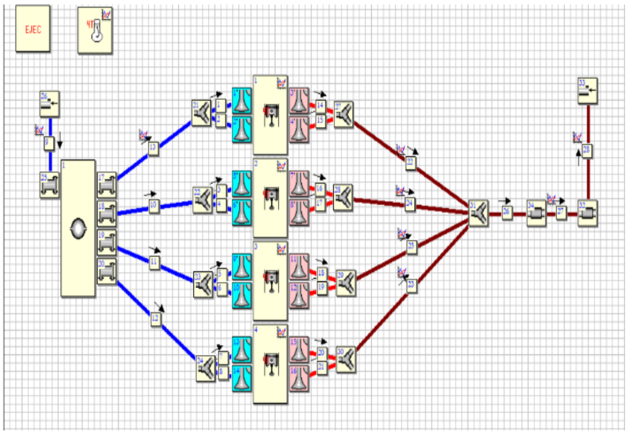

Figure 1. OpenWAM 4-1 configuration.

In Fig. 2, the configuration 4-2-1 presented, the cylinders were phased out 360 °according to the order of ignition, and in this case, the cylinders 1-4 and 2-3 was joined together, to be then assembled in a final manifold. Table II shows the lengths and diameters used in the 1D simulation of the original exhaust manifold and the different configurations analyzed [7].

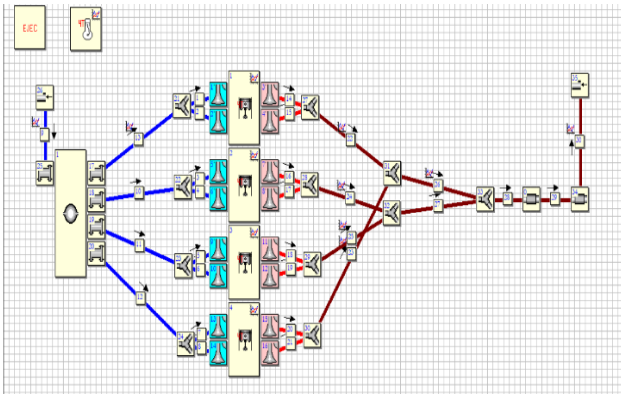

Figure 2. OpenWAM 4-2-1 configuration.

The original exhaust manifold is made of two cast iron parts using a 4-2-1 configuration; initially it joins cylinders 1-4 and 2-3 in primary ducts with an average length of 273 mm, and then connect them in secondary ducts 318 mm in length.

TABLE II. EXHAUST MANIFOLD PARAMETERS IN SOFTWARE 1D

Parameter	Original		4-1	4-2-1	
	Primary	Secondary		Primary	Secondary
Input diameter (mm)	35	31	35	35	41.45
Length (mm)	L1: 312 L2: 277 L3: 244 L4: 259	318	650 a 800	250 a 400	250 a 400
Outlet diameter (mm)	35	31	35	35	41.45
Numerical method	Lax Wendroff				

C. Dynamometric Testing

To determine the power and torque experimentally, the MAHA brand dynamometer (Maschinenbau Haldenwang) LPS 3000 used, developing the tests at 2850 meters of altitude. The dynamometric tests performed according to INEN 960, based on ISO 1585 and ISO 3173 [18]. Vehicles characteristic curves obtained from five test, one for each exhaust manifold analyzed, applying a specific test protocol. A correction factor applied according to ISO 1585, JIS D 1001 or SAE J 1349. The correction factor α_a, is given by Eq. (1).

$$\alpha_a = (\frac{99}{P_p})^{1.2} * (\frac{T_p}{298})^{0.5} \qquad (1)$$

Where were the barometric pressure and temperature, respectively, at the test site by geographic location conditions. To evaluate statistically if the obtained results have significant difference and select the best variant, the STATGRAPHICS Centurion XV software (Trial version 15.2.06, Stat Point Inc., USA) was used [19]. For the experimental design a multifactorial design was used, where the independent variables are determined by the type of configuration of the exhaust manifold (3 variants) and the number of revolutions of the MCI (3 revolutions); and as dependent variables the power and torque.

III. RESULT AND DISCUSSION

A. Results of Dimension 1D Simulation

The Configuration 4-1 was analyzed by varying the length of the pipe from 650 to 800 mm in steps of 25 mm. The length 775 mm allows to reach the highest power, as shown in Fig. 3. Configuration 4-2-1 was initially analyzed at 6500 rpm, modifying the length of the manifold in a range of 250 to 400 mm, for both primary and secondary segments. From the combinations segments a 350 mm was selected for the primary and a 400mm for the secondary, since those reaches greater power as shown in Fig. 4. The lengths selected for the 4-2-1 and 4-1 configuration were simulated in the range of 2500 to 7500 rpm of the motor [20].

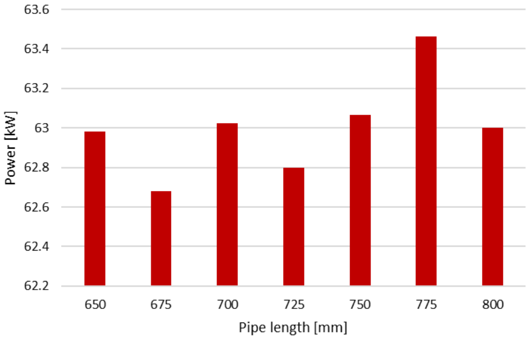

Figure 3. Power comparison for lengths between 650 to 800 mm, every 25 mm.

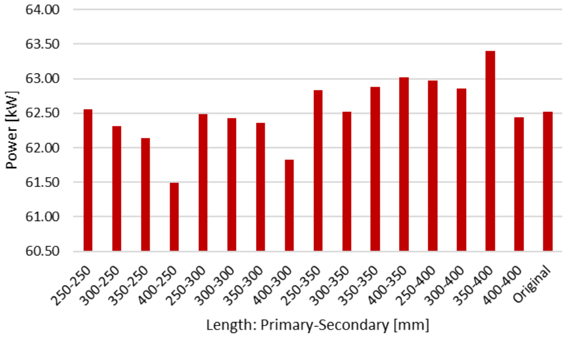

Figure 4. Power comparison for several dimensions in the 4-2-1 configuration.

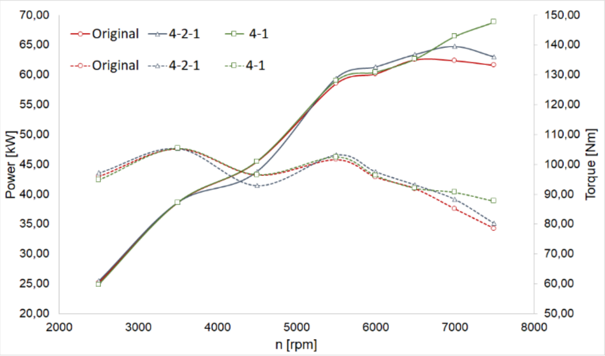

Figure 5. Engine characteristic curves according to 1D simulation.

The engine characteristic curves obtained from the 1D simulation for the original exhaust manifold, configuration 4-2-1 and 4-1, are shown in Fig. 5. The 4-2-1 configuration allows better engine performance results in the range of 5500 to 6500 rpm, generating a maximum power increase of 3.57 %; while the 4-1 configuration does so over 6500 rpm with an increase 10.1 % over the original, confirming what has stated by Jawad and Montenegro [21-22].

B. Exhaust Manifold Manufacturing, Configuration 4-1

Type A consists of bending the tubes using a hydraulic bender as shown on Fig. 6 left side, this produced deformation in the cross-section in the bends. Type B, known as the step header, Fig. 7 right side, was built by welding the pre-bent pipe sections, and keeping the circular section of the pipe constant. The 38.1 mm diameter, 775 mm long round pipe exhaust manifold was constructed for each duct in 1.5 mm thick ASTM A500 steel, coated with a high temperature paint layer to prevent corrosion.

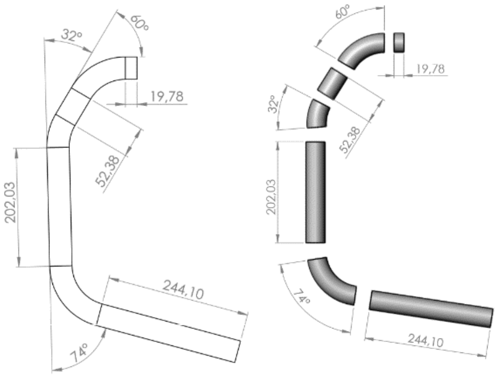

Figure 6. Conduit blueprints: bent type A (left), sectioned B type (right).

C. Results Dynamometer Test

Tubes that maintain a uniform diameter, such as those curved with a bending mandrel, improve performance over pipes with poor bending or wrinkling [23-24]. In Fig. 7, the engine power and torque curves shown when using the original exhaust manifold and the 4-1 construction configuration type A and B. The construction method strongly influences; it shown that type B contributes to better engine performance for dynamometer test [25].

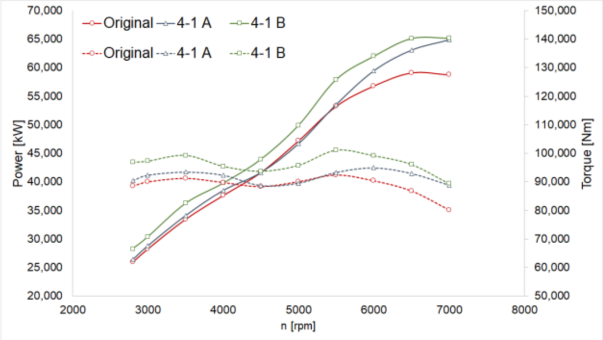

Figure 7. Engine performance for dynamometer test.

Table III shows the statistical results of the comparative with respect to power. The ANOVA table shows the P-value of the F-test with less than 0.05 indicating a statistically significant difference between the means of the 3 variants with a level of 95.0% confidence.

TABLE III. ANOVA TABLE FOR POWER (ORIGINAL, 4-1 A AND 4-1 B)

Source	Sum of squares	Gl	Middle Square	Ratio-F	Value-P
Between groups	828.208	8	103.526	1184.08	0.00
Intra groups	3.14754	36	0. 0874317		
Total (Corr.)	831.356	44			

To determine which means are significantly different from others, Multi-Range Tests selected. The homogeneous groups represent a significant difference between all the groups being the 4-1 B the one with a better behavior for all engine speed analyzed, for the 5500 rpm case there is no significant difference between the original manifold and 4 -1 A. This can be seen in Fig. 8.

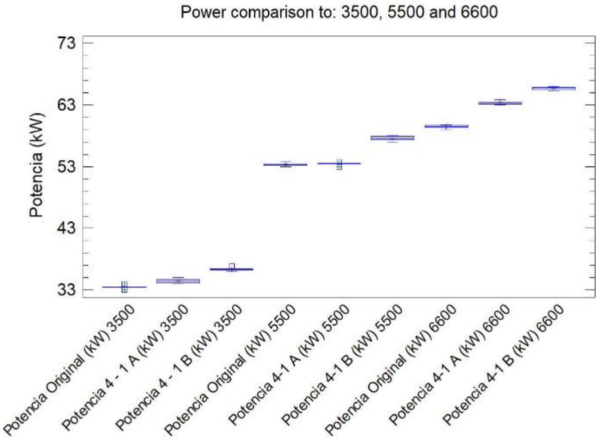

Figure 8. Box and whiskers chart for power (Original, 4-1 A and 4-1 B)

Table IV shows the statistical results of the comparative with respect to torque. As in the case of power, the P-value of the F-test is less than 0.05; indicating that there is a statistically significant difference between the mean of the 3 variants [19]. To determine which means are significantly different from others, Multi-Range Tests selected. The homogeneous groups represent a significant difference between all the groups being the 4-1 B the one with a better behavior for all rpm analyzed. This can also be seen in Fig. 9.

TABLE IV. ANOVA TABLE FOR TORQUE (ORIGINAL, 4-1 A AND 4-1 B)

Source	Sum of squares	Gl	Middle Square	Ratio-F	Value-P
Between groups	828.208	8	103.526	1184.08	0.00
Intra groups	3.14754	36	0.0874317		
Total (Corr.)	831.356	44			

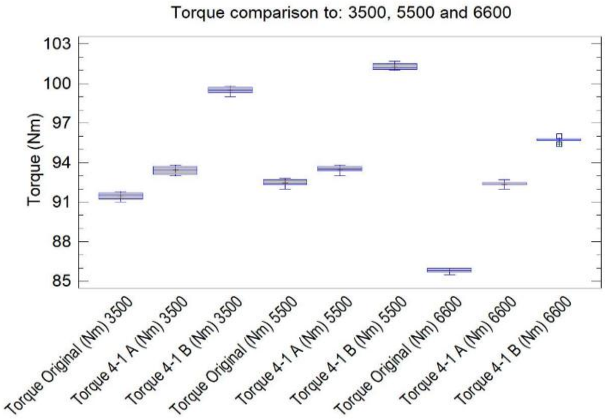

Figure 9. Box and whiskers (Original, 4-1 A and 4-1 B).

D. Correlational Computational Results vs Experimental Test

The results obtained by the computational method and those obtained experimentally with respect to the original multiple are shown in Fig. 10 [26], with a variation of less than 9 % being identified; it also can be noticed a similarity on the shapes of the curves.

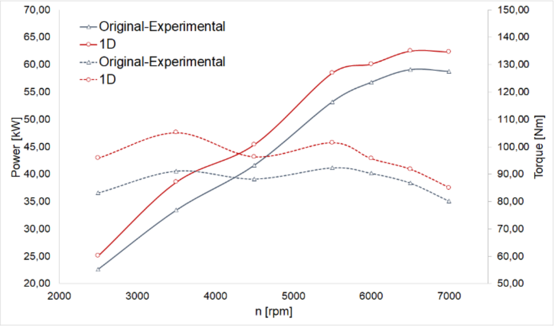

Figure 10. Engine characteristic curves for the original 1D simulator and the dynamometric test.

Fig. 11 shows the curve developed in the dynamometer for manifold type A with an average difference of 8 % against the curve obtained from the computational process; while the type B has a lower average variation, close to 4%, and with a minimum error of 2 % in the area of interest, i.e., where the power is maximum. Within the Open WAM simulation, the pipe diameters considered constant throughout the multiple path, so the results are more similar to the type B construct, in agreement with what Callies and Ayala say [27-28].

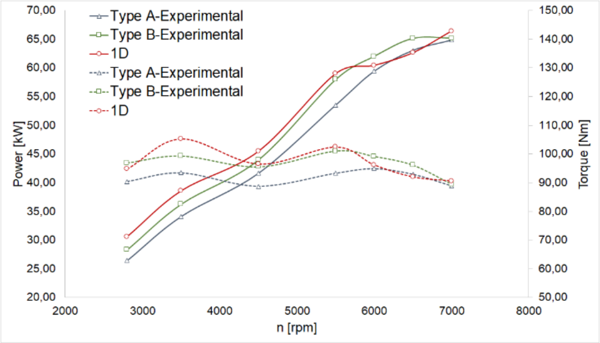

Figure 11. Comparison of motor characteristic curves for multiple 4-1 of the 1D simulation and the dynamometric test.

IV. CONCLUSIONS

In conclusion, a method for assessing engine performance was presented by varying the configuration of the exhaust manifold and dimensions by means of the 1D simulation, which allows for greater power and torque in the G13B engine of the Suzuki Twin Cam 1.3.

The proposed exhaust manifold, configuration 4-1, increases the maximum power with respect to the original system by 8.41% and 10.33 %, according to type A and type B constructions, respectively; as well as a torque increase of 3.26 % for type A and 8.83% for type B; the most significant contribution to engine performance is in high revolutions, i.e., over 5000 rpm.

The exhaust manifold construction technique significantly influences the performance of the engine, with type B being the most optimal with statistically significant differences in relation to the other configurations. The manifold design responds positively to the needs of the racing vehicle, where the engine maintained at high revs throughout the ride.

Finally, the methodology used by the one-dimensional simulation proved to be a useful tool to predict engine performance, with minimal difference of 2% in results and characteristic curves, compared to the experimental data obtained in a dynamometer test.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mr. JC. Rocha, as the main author, conducted simulation and research wrote the manuscript. Mr. ES. Arroyo, growth experimental research. Dr. E. Llanes organized, promoted, and revised the research. Mr. W. Vega, revised the research and experimental research. Mr. G. Moreno, wrote and translated the manuscript. All authors had approved the final version.

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