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INERTIAL DYNAMOMETER TEST RIG FOR SMALL, HIGH PERFORMANCE ENGINES

The paper presents a general idea of the acceleration test method and the design, construction and testing of the inertial dynamometer test rig developed for small, high performance two-stroke engines. The method is universal and can be also used for four-stroke engines but it is especially useful for the two-stroke ones. The testing procedure is described and the advantages of that type of investigation method are pointed out. It has been proved that the reliability of the method is satisfactory. It was also proven that the individual construction of the inertial dynamometer of good quality can be performed individually and that it can be a very useful investigation tool in engine tuning practice. The point has been stressed that the major advantage of that method is the possibility of the instantaneous measurement of the engine power characteristic during unsteady engine operation (acceleration) where the time for the single run does not exceed ten seconds.

1. Introduction

The two-stroke engines are very advantageous in high performance competition applications because of their potential to assure high power output, relatively low mechanical complexity and, by that, low weight. Two-stroke engines are therefore very popular for road racing motorcycles and high performance karts, snowmobiles etc. Power output of the engines especially tuned for motor sports can be as high as 250 kW per one liter of the displacement volume at engine speed significantly exceeding ten thousand revolutions per minute. Then, high power output of that type of engines results in very high thermal and mechanical stresses of their elements. Because of that,

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their durability is remarkably reduced and therefore they have to be used economically, and their testing procedures ought to be as short as possible.

The high engine power output is usually achieved during a time consuming process of testing procedures performed in most cases with the use of the engine test rigs. The aim of that type of investigations is not only to obtain the maximum power output but also (and sometimes – first of all) to get the most suitable characteristics of the engine output parameters [1]. In the light of the imperfection of all the existing calculation methods (and in most cases – their absence at all) the only way to tune the engine is to run a large number of tests and to analyse the engine power output after each change of engine design details, each modification of the flow characteristic of the working medium through the engine (intake and exhaust systems), and the adjustment of the engine regulation parameters [2], [3], [4], [5].

The use of conventional engine dynamometers in the course of tuning of small high-performance two-stroke engines does not give correct results because of the following reasons.

- Conventional, steady state testing methods are based on the measurements of the engine torque in a sequential number of the test points. It requires a certain time to reach the steady state conditions at each test point, and the highly tuned engine usually can not stand it even if it is water cooled. Research experience shows that this type of testing makes it necessary to enrich excessively the mixture and to retard the spark advance. This can diminish the thermal load of engine elements but the results significantly depart from the reality.
- The complexity of the thermo- and the gasdynamics phenomena which compose the engine working cycle and the fact that in the two-stroke engine the intake, combustion and exhaust processes overlap inside the cylinder during the single crankshaft revolution create the conditions in which the gas flow is strongly dependent on the pressure wave action in the inlet and exhaust tracts. This wave action, and by that also the engine performances depend, in turn, on the thermal state of the gas in the intake and exhaust systems which is established during the unsteady, dynamic processes of the charge exchange during engine acceleration and deceleration. This is the major reason why the repeatability of the results obtained in the course of steady state testing is not satisfactory and the values of the parameters measured in that way (torque, power) sometimes remarkably depart from reality.
- An additional difficulty can be created by some auxiliary devices used in the performance engines which adjust "on-line" (in a mechanical way) the intake and exhaust system characteristics to the actual engine conditions. When the engine operating conditions are changing quickly, the action of those devices will be remarkably delayed. None of the steady testing procedure is able to take it into account.

- During the steady state testing, the experimental points are selected at the predetermined interval of the independent variable (for instance with the increment of 500 or 1000 rpm). In two-stroke high performance engines, however, the engine characteristics do not have to be smooth all the way and significant local variations can appear. They can be very important from the standpoint of the engine performance, but might not be noticed during the steady state testing.

All the arguments mentioned above indicate that for the testing of the high performance two-stroke engines it is necessary to use such a test method that would allow for creating the conditions of engine loading similar to those existing on the racing circuit.

2. Inertial dynamometer

Measurements of the engine performance under acceleration conditions can be done with the use of an inertial dynamometer. The idea of that type of the engine testing is well known for many years but inertial dynamometers have never been commercially available. The inertial test rigs, existing in small numbers, have always been constructed individually [6]. Because of that the literature on that subject is extremely limited and the experience gained in the process of test rig development is not spread.

The objective of this paper is to fill up this gap. In the paper, design project and practical realization and testing of an inertial dynamometer test rig is presented, developed for testing high performance kart engines of displacement volume up to 125 cu cm and power output up to 50 kW.

2.1. General idea

The inertial dynamometer test rig makes it possible to measure the engine power output characteristics under the conditions that are equivalent to the conditions during the kart acceleration on the racing circuit. Here, the inertia of the kart is substituted by the inertia of the flywheel of an appropriate moment of inertia, mechanically coupled with the engine crankshaft. Let us first assume that the flywheel is directly coupled with the engine crankshaft. During the test, the engine full throttle opening is increasing the rotational speed of system engine-flywheel from n_{min} to n_{max} and the diagram of change of the engine speed with time is registered. It is possible to convert the diagram for the typical frequency characteristics of the engine torque M_e according to the formula:

$$M_e = I_N \cdot \omega_e + M_0 \tag{1}$$

where: I_N – moment of inertia of all rotating masses; ω_e – engine crankshaft angular velocity; M_o – moment of mechanical losses.

Knowing the numbers for I_N and M_o and assuming that the mechanical losses do not depend on rotational speed, one can determine the acceleration characteristics of the system in order to obtain the characteristics of the engine torque. The use of computer makes it practically possible to register the engine speed at time intervals of about 1 ms. When the moment of inertia of the flywheel is determined correctly, the whole data registration process for a single test takes not more than ten seconds. The engine works during that time under conditions that imitate well those of kart acceleration.

2.2. Simplified testing procedure

Let us again assume that the flywheel is directly coupled with the engine crankshaft (intermediate rotating elements are neglected) and that there are no shear losses ($M_0 = 0$). The energy increment of the rotating system between two sequential test points j-1 and j (corresponding to acceleration times t_{j-1} and t_j) is:

$$\Delta E_j = \frac{1}{2} \cdot I_f \cdot \left(\omega_j^2 - \omega_{j-1}^2\right) \tag{2}$$

where: I_f – flywheel moment of inertia; ω- angular velocity of the engine-flywheel shaft which is:

$$\omega = \frac{\pi \cdot n}{30} \tag{3}$$

and

$$I_f = \frac{1}{2} \cdot m_f \cdot r_f^2 \tag{4}$$

where: m_f and r_f are the mass and the radius of the flywheel.

The engine power output from the engine shaft for the j-th point:

$$N_{ej} = \frac{\Delta E_{ej}}{\Delta t_j} \tag{5}$$

Continuing this procedure from n_{min} to n_{max}, one obtains a series of points $N_e = f(n_e)$ that constitutes, after smoothing treatment, the power characteristics of the engine.

This procedure can be only considered as the first approximation because the influence of all the intermediate elements between engine and the flywheel: the inertia of other rotating parts and their mechanical losses (for instance the inertia of the intermediate shaft, efficiency of the chain gears, mechanical losses in bearings and the shear losses of the rotating elements in the air) was temporarily neglected. This simplification does not allow for determining of the true engine power characteristics. The point has to be stressed, however, that the investigations of the racing engines are, in general, comparative in nature. The researcher looks for the answer whether the presently measured engine characteristic is "better" than those obtained previously at different sets of input parameters (design or regulation). The absolute values of the measured torque or power are here of the secondary importance. The evaluation of the "quality" of the obtained engine characteristic is highly subjective and must be always confronted with the engine dynamics on the racing circuit.

2.3. Test rig scaling

If there is a need for the true values of measured engine output parameters, then it becomes necessary to consider the acceleration work of all the rotating elements and to evaluate losses. Sometimes it is also necessary to include the power used for driving the additional engine equipment (for instance water pump).

Instead of determination the inertia of each of the rotating elements of the test rig and the subsequent calculation of the overall inertia of the whole system it is much more practical to apply the following procedure.

The work to accelerate the whole system up to the angular velocity ω_f of the flywheel is:

$$W = \frac{1}{2} \cdot \sum_{l=1}^{l} I_l \cdot \omega_l^2 + t \cdot \sum_{l=1}^{l} \sum_{k=0}^{k} \mu_{lk} \cdot \omega_l^2 \tag{6}$$

Where: I_l – momentum of inertia of the l-th rotating element; ω_l – angular velocity of the l-th element with the inertia I_l; t – acceleration time; μ_l – shear losses of the l-th element proportional to the k-th power of its angular velocity ω_l.

Knowing the kinematical relationships of the flywheel drive train we have:

$$\omega_l = i_l \cdot \omega_f \tag{7}$$

and

$$\omega_l^2 = i_l^2 \cdot \omega_f^2 \tag{8}$$

Substituting:

$$W = \frac{1}{2} \cdot \omega_f^2 \cdot \underbrace{\sum_{l=1}^{l} I_l \cdot i_l^2}_{I_N} + t \cdot \underbrace{\sum_{l=1}^{l} \sum_{k=0}^{k} \mu_{lk} \cdot \omega_f^2 \cdot i_l^2}_{\mu} \tag{9}$$

where: I_N and μ are overall, unknown: moment of inertia and shear losses, respectively.

This work must be equal to the work of the engine:

$$N_e \cdot t = \frac{1}{2} \cdot \omega_f^2 \cdot I_N + t \cdot \mu \tag{10}$$

The determination of the overall inertia I_N can be done during two acceleration tests of the whole setup. One of the tests has to be performed when the auxiliary mass with well known moment of inertia I_d is added to the system. During the tests two values of the total system acceleration time t_1 and t_2 are measured without and with the additional mass, respectively.

Thus:

$$N_e \cdot t_1 = \frac{1}{2} \cdot I_N \cdot \omega_f^2 + t_1 \cdot \mu \tag{11}$$

And:

$$N_e \cdot t_2 = \frac{1}{2} \cdot I_N \cdot \omega_f^2 + \frac{1}{2} \cdot I_d \omega_f^2 + t_2 \cdot \mu \tag{12}$$

Rearranging and simplifying:

$$I_N = \frac{I_d \cdot t_1}{t_2 - t_1} \tag{13}$$

Now, the new value of I_N has to be used for further calculations, and the calculated torque and power characteristic becomes identical with the true ones. It would be impossible to obtain this type of the engine characteristic with the use of the conventional, steady state dynamometer method because of the reasons briefly mentioned in the introduction.

3. Design of the inertial dynamometer

3.1. Kinematics of the test rig layout

The basic aim of the work was to design the test rig in order to perform individual tests in an easy way.

The schematic of the test rig general layout is presented in figure 1. The engine (1) is coupled with the intermediate axis (2) with the use of the chain drive (3). The second chain drive (4) is transmitting the power to the flywheel (5) fixed to the flywheel shaft (6). The electromagnetic clutch (7) makes it possible to disconnect temporarily the flywheel from the engine. The hydraulic disc brake (8) acting on the axis (2) allows for the quick stopping of all the rotating elements. The water pump (optional, 9) is driven from the axis (2) by the set of two rubber belts. The steel disc with magnetic sensor (10) is fixed to the flywheel shaft (6) and it serves as the source of signals used to register the flywheel speed.

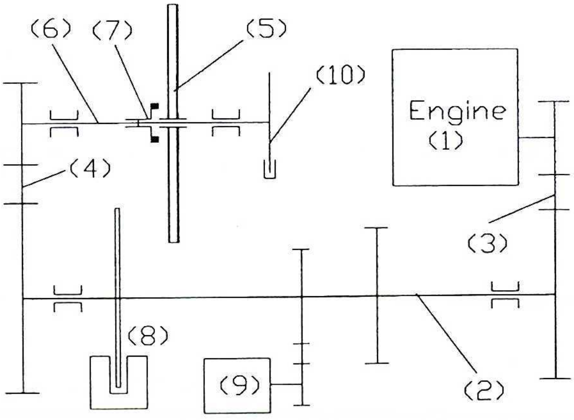

Fig. 1. Schematic of the test rig general layout

The described layout of the test rig was selected among several different possibilities. The direct coupling of the engine crankshaft with the flywheel axis has not been accepted because if would remarkably reduce the universality of the rig: engines with either left or right side crankshaft sprocket could only be tested. The double chain gear made it possible to preserve the original crankshaft-intermediate axis (2) speed ratio and to assure the high flywheel speed, reducing by that its mass. The second chain gear ratio was set to 5. If it was equal to 1 (the flywheel fixed directly to the intermediate axis) the flywheel mass should be five times greater than before, and it would result in a very heavy slowly rotating flywheel. The whole test rig would be also very heavy in that case. Such elements as: the intermediate axis, the disc brake, the water pump, the chain gears, the clutch and the set of bearing housings were taken from the kart and adopted for this measurement setup.

The electric starter coupled with the intermediate axis allows for easy start-up of the engine.

3.2. Determination of the flywheel dimensions

The test rig should be able to create the engine running conditions similar to those existing on the racing circuit. The kart accelerates from the velocity V_I to the maximum velocity V_{max} during time t. In the course of the test with the use of the inertial dynamometer the engine accelerates the flywheel from n_I to n_{fxma}. To keep the acceleration time constant, the condition of energy equality of the kart and the flywheel must be satisfied:

$$E_k = E_f \tag{14}$$

If m_k is the total mass of the kart with the driver, the maximum kinetic energy of the kart is:

$$E_k = \frac{1}{2} \cdot m_k \cdot V_{\max}^2 \tag{15}$$

Maximum kinetic energy of the flywheel is:

$$E_f = \frac{1}{2} \cdot I_f \cdot \omega_{f\max}^2 \tag{16}$$

Hence

$$I_f = \frac{1}{2} \cdot m_f \cdot r_f^2 \tag{17}$$

where: m_f and r_f – the mass and the radius of the flywheel,
therefore

$$E_f = \frac{1}{4} \cdot m_f \cdot r_f^2 \cdot \omega_{f\max}^2 \tag{18}$$

Remembering that

$$\omega_{f\max} = \frac{1}{30} \cdot \pi \cdot n_{f\max} \tag{19}$$

and rearranging we obtain the expression for the mass of the flywheel:

$$m_f = \frac{1800 \cdot m_k \cdot V_{\max}^2}{\left(\pi \cdot n_{f\,\max} \cdot r_f\right)^2} \tag{20}$$

Assuming that: $r_f = 0.15$ m, $n_{fmax} = 15000$ rpm, $V_{max} = 150$ km/h (42 m/s) and $m_k = 180$ kg, the mass of the flywheel should be $m_f = 11.45$ kg. The thickness of the steel flywheel therefore should be about 0.02 m. The presence of some intermediate rotating elements does not change these values significantly, because of elements' low weight, small radius and low rotation speed, much lower than those of the flywheel.

The torque that the clutch is able to transmit determines the maximum engine power which can be considered for testing. With the total gear ratio of $i = 1.25$, the maximum power of the engine tested can not exceed $N_{max} = 50.3$ kW.

3.3. Design project

The assembly drawing of the inertial dynamometer test rig is presented in figure 2. A simplified overview of single cylinder air cooled kart engine, without the gearbox is shown in the drawing. The engine mounting has been designed in such a way that it is possible to use any type of the kart engine with displacement volume up to 125 cu cm, water or air cooled, with or without the gearbox. Universality of the design is confirmed by the fact that it is possible to investigate engines with left or right side position of the chain sprocket.

The test rig is provided with all the necessary equipment: the fuel tank, the support for the exhaust system, the steering levers, the safety screens, the water cooler etc. All the test rig elements are mounted in a heavy and rigid frame.

The electromagnetic clutch (7) is applied in order to make it possible to disconnect temporarily the flywheel (for instance during the start-up of the engine) and also – to protect the flywheel axis (6) from the excessive load. The clutch is able to transmit the torque up to 40 Nm. It is also possible to use an external, portable starter.

In the course of practical construction of the test rig, a position of the disc brake have been changed. Because of the relatively narrow flywheel it was possible to use it directly as the disc for the brake.

The general view of the assembled inertial dynamometer test rig is presented in figure 3. The high performance kart engine "TM Racing", single cylinder, water cooled, equipped with the six step gear box, with the power output exceeding 40 HP was mounted in the rig.

The test rig is compact, freely standing, mobile experimental setup. It co-operates with a mobile computer data acquisition system, whose software provides ready-to-analyse, smoothed engine power profiles.

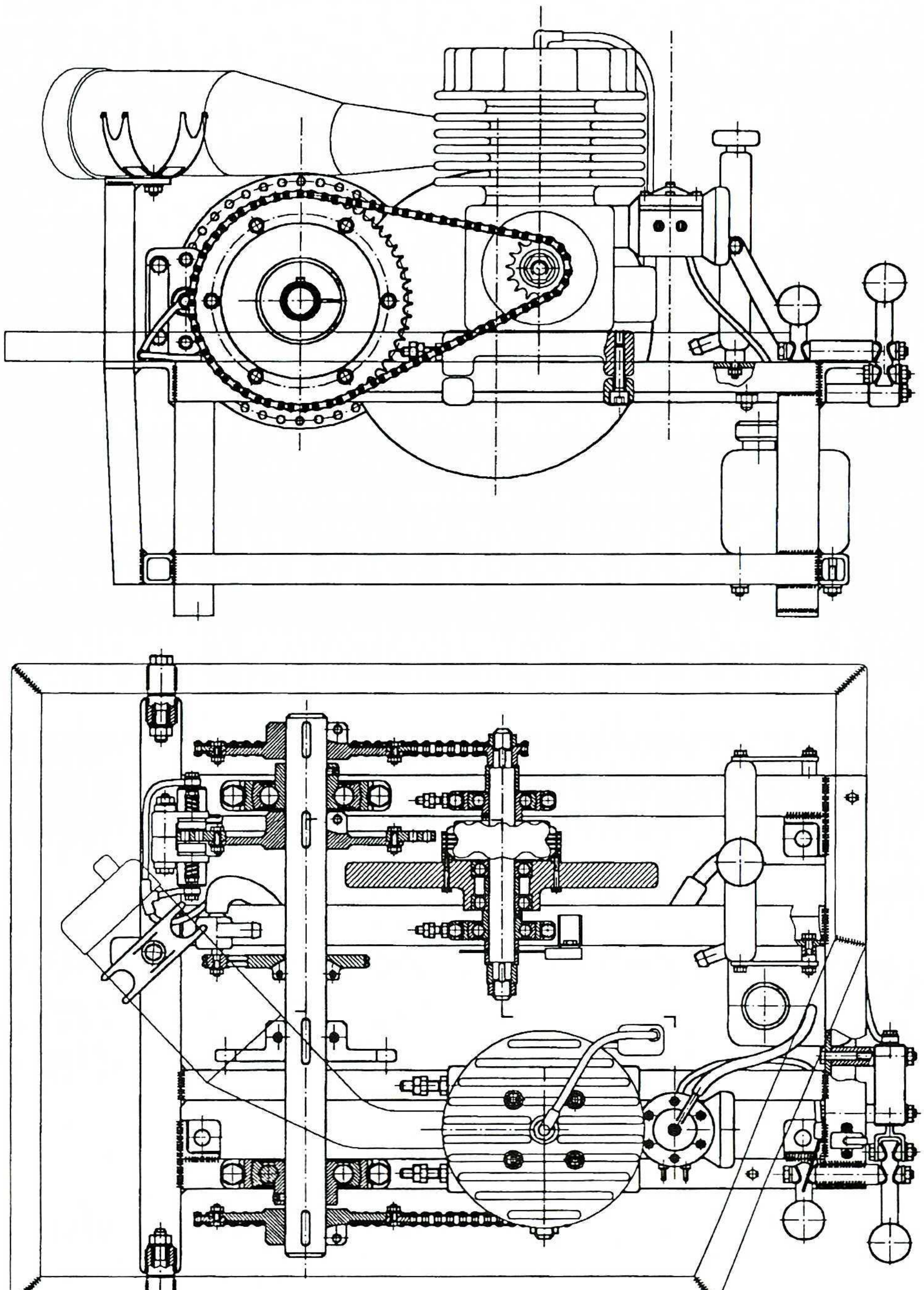

Fig. 2. Design drawings of the inertial dynamometer test rig

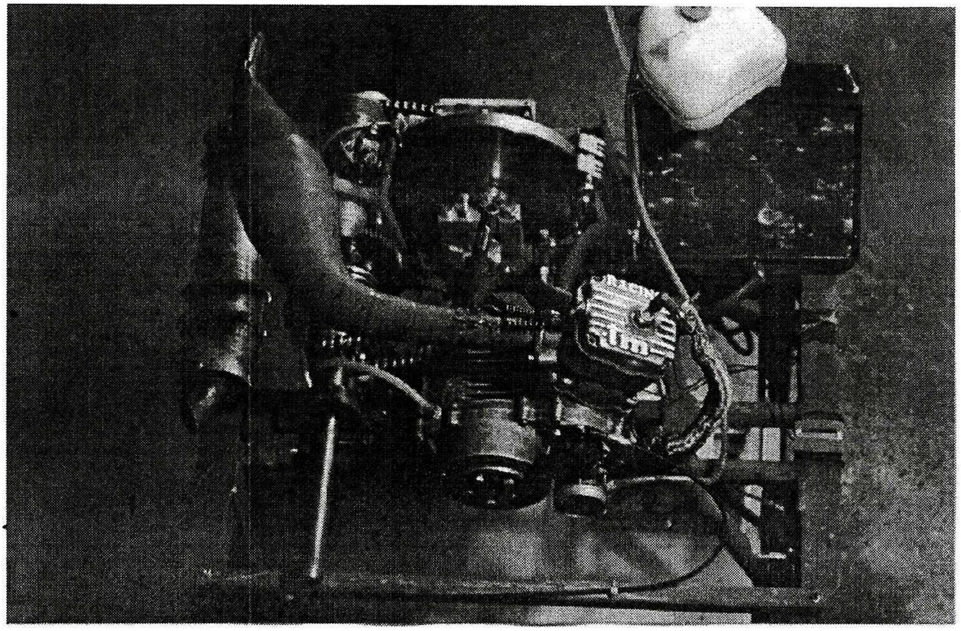

Fig. 3. Photograph of the test rig

3.4. Engine testing procedure

The testing procedure consists of the following steps:

Engine start-up. Turning the engine on is done with the use of the electric starter coupled to the intermediate axis when the flywheel is disconnected by the clutch action.

Warm up period. The engine works idle for a couple of minutes until it reaches the required temperature at which its operation is stable. The decision of terminating the warm-up belongs to the engine operator, because it is well known that full stabilization of high performance two stroke engine at idling conditions is not possible.

Test. The run of the test begins at the moment of activation of the clutch that connects the flywheel with the engine crankshaft, simultaneously with full opening of engine throttle. The system engine-flywheel accelerates and its rotational velocity changes from idling speed to its maximum value. The whole testing during a single run takes no more than ten seconds. Then the engine throttle is closed and the rotating parts of test rig are brought to a standstill with the use of the disc brake.

Data registration. In the course of the test, the time dependence of rotational speed of the flywheel is registered. The registered data are converted into time (or crank angle) characteristic of the engine power. All the input parameters of the engine and the test rig, previously stored in the computer memory, are taken into account.

4. Examples of test results

4.1. Power characteristics

The example of the measured profile of engine power versus engine speed is presented in figure 4. The power has been here expressed in units of horse power (HP). This was done on purpose to facilitate direct comparison of the obtained results with some other available engine data. The values of the engine work done within the specified interval of engine speed are also printed. These data are very useful from practical point of view, because the engine characteristics can be confronted with the behavior of the kart on the racing circuit. Sometimes it is better to choose the engine characteristics with remarkably lower maximum power output having instead a greater engine work at lower engine speeds, because it fits better to a given geometry of the circuit.

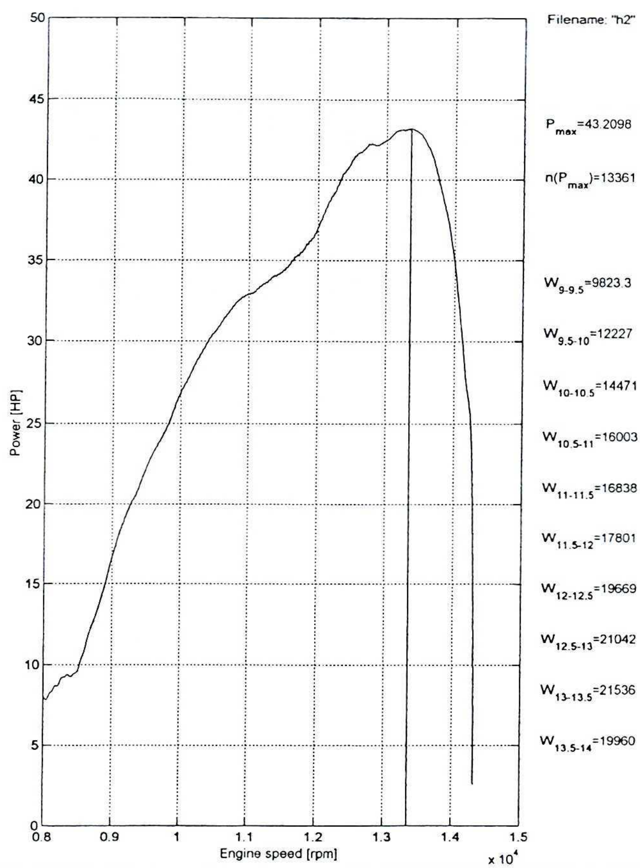

Fig. 4. Example of engine power characteristic

Three power characteristics of the same engine are juxtaposed in figure 5, each of them obtained for a different length of the exhaust system. The highest power output was obtained with the exhaust system B at the engine speed $n = 13\,300$ rpm . It was revealed in practice, however, that engines with higher power values within a wide range of lower engine speeds are much more useful for most of kart circuits than those with very high value of the peak power.

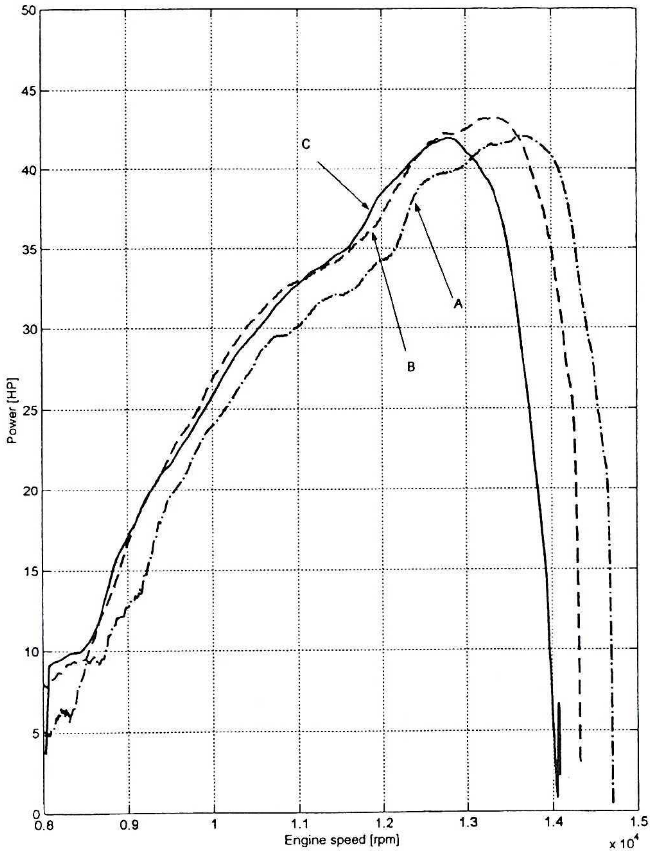

Fig. 5. Comparison of engine power profiles for three different lengths of the exhaust systems: A – 670 mm; B – 650 mm; C – 690 mm

4.2. Measurement accuracy

As it was mentioned before, the knowledge of absolute value of engine power is not of primary importance for that type of racing engines. Much more important is the possibility of comparing the engine characteristics for a given set of the design end regulation parameters. Final selection of one particular have a really good repeatability of the measured engine characteristics to be sure that the measurements are reliable. To check the repeatability of the measurements, twelve consecutive tests were run, and the twelve engine characteristics were drawn in the same diagram. It was impossible to observe the dispersion of results between the consecutive runs because all the lines lied within the width of the printer line. Several tests of this type were performed and the results were always the same. The repeatability of the measurements was therefore assessed as more than satisfactory.

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Hamownia bezwładnościowa dla małych silników wyczynowych

Streszczenie

W pracy przedstawiono zasadę działania i projekt techniczny hamowni bezwładnościowej dla małych, wyczynowych silników spalinowych. Przedstawiono również wykonane stoisko hamowniane oraz procedurę testowania silników na przykładzie wyczynowego silnika kartingowego. Omówiono zalety takiej metody badawczej w zastosowaniu do silników wyczynowych. Udowodniono, że jednostkowe zbudowanie hamowni tego rodzaju jest stosunkowo łatwe i jest możliwe w warunkach amatorskich. Wykazano, że dokładność uzyskiwanych wyników jest dobra oraz, że taka metoda badawcza jest wysoce przydatna dla kształtowania charakterystyk częstotliwościowych małych silników wyczynowych. Podkreślono zasadniczą zaletę takiej metody badań do tego zastosowania, którą stanowi możliwość testowania silników w warunkach dynamicznych, zbliżonych do tych, które występują na torze wyścigowym.