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SIMULATION OF PNEUMATIC MOTOR USED IN PNEUMOBILE

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Abstract

One of the alternative powertrain systems of cars, commercial vehicles and mobile machines are hybrid drives with pneumatic motors for compressed air. This paper presents a mathematical model and the results of simulation calculations of piston pneumatic motor. Mathematical model was based on the fundamental principles of mechanics, thermodynamics and rights of airflow. For simulation model parameterization, prototype of such engine was built and installed on dedicated test stand. Performed experimental research allowed achieving values of coefficients and components characteristics used for model estimation. One of the important tasks of this study was to create the control system of the compressed-air supplied engine. For this purpose an appropriate pneumatic and electronic component were selected and also an algorithm was created which would facilitate changing of the engine settings in order to obtain the best performance. Using elaborated simulation model, series of calculation were performed for different parameters of pneumatic motor, like cylinders diameter and stroke, length of the crank, compressed air pressure and valves size. A lot of attention was devoted to determine the influence of control system settings, such as valves opening and closing in reaction to crankshaft position, on motor properties. When discussing the results of calculations considerable attention was paid to the power, torque and efficiency values. To illustrate performance of designed engine, simplified model of light vehicle was used to calculate possible to achieve acceleration, velocity and travel distance.

1. Introduction

As long as vehicles exist, engineers try to find out the best solutions to propel them. The internal combustion engines are commonly mounted in cars, but there are many restrictions, that they have to fulfil, due to ecology standards and noise limits [9]. Limited sources of fossil fuels cause an increase in prices of petroleum and diesel, so reduction of their consumptions will be beneficial for economic reasons. Alternative sources of energy could solve many problems. There are many types of engines, but not every of them could be used in drivetrain of the vehicles. New technologies are still developed, so meantime, to solve problems with energy storage and infrastructure of charging stations, the “hybrid vehicle” was created. Usage of two (or more) power sources provides cars many advantages such as increased range, less fuel consumption and higher independence in comparison to vehicles using one type of engine only. Three basic types of hybrid vehicle drive structure can be listed: parallel, series and series-parallel, also called power-split. The last one is the most universal, due to the possibility of using both energy sources in the highest degree. Certainly, the most popular layout of hybrid vehicle is combination of internal combustion engine with electrical drive, due to high efficiency of electric motor. However, it has some disadvantages too, for example heavy, toxic and expensive to manufacture batteries.

Hybrid Air is power-split hybrid motor designed by Peugeot S.A. (PSA) in cooperation with Bosch GmbH, which consists of internal combustion engine, hydraulic motor and hydro-pneumatic accumulator. The name “Hybrid Air” comes from the type of energy source - the piston accumulator, in which one chamber contains compressed air, which provides force on the hydraulic fluid stored in second chamber, connected with hydraulic system. This system can recover more energy than electric hybrids [2] and is cheaper, and easier to manufacture. Usage of hydraulic motor in vehicle is not new idea, but so far it has been used nearly only in heavy trucks, shuttles and buses [3].

To propagate and improve compressed air drive technology, Bosch Rexroth the Drive and Control Company, since 2008, organizes "Pneumobil" competition [8]. For this competition, each team have to build vehicle propelled by linear, pneumatic actuators. Presented in this paper pneumatic motor was designed for such vehicle, but can also be used to other applications. Constructed engine has three-piston design structure and uses typical pneumatic cylinders mounted in one line. Of course, it is beneficial to use three actuators instead of two or four, because it gives smaller torque oscillations in each rotation of the crankshaft. Parameters of engine were selected due to fulfil the vehicle properties such as its acceleration and range of operation – distance.

2. Mathematical model

The mathematical model of the pneumatic engine was simplified to model of the system with one degree of freedom (DOF) mobility, reduced to the crankshaft axis:

$$J_{zr}\frac{d\omega}{dt} = \sum_i M_i \,, \tag{1}$$

where:
J_{zr} – moment of inertia, reduced to the crankshaft,
$\frac{d\omega}{dt}$ – angular acceleration,
M_i – torque generated by particular i cylinder,
i – cylinder number.

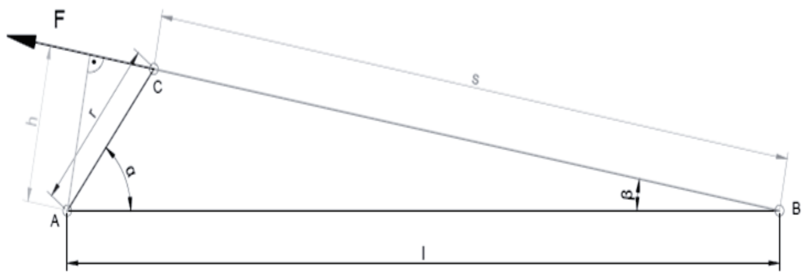

Fig. 1. Cylinder force direction in pneumatic motor structure

Torque generated by selected pneumatic cylinder (cylinder force direction is presented in Fig. 1) is represented by equitation:

$$M_i(\alpha) = F(\alpha) * \frac{l*r*\sin\alpha}{\sqrt{r^2+l^2-2*r*l*\cos\alpha}}, \tag{2}$$

where:
$F(\alpha)$ – cylinder force,
α – angle of crankshaft rotation,
r, l – dimensions of the engine.

Force of the actuator is represented by the formula [5]:

$$F = p_1A_1 - p_2A_2 - sgn(v_s) * F_t, \tag{3}$$

where:
p_1, p_2 – pressure in piston and rod chambers of the actuator,
A_1, A_2 – areas of piston for each side,
v_s – piston velocity,
F_t – friction force.

To determine pressure values in particular chambers of the pneumatic cylinder it is necessary to use continuity equation. To simplify mathematical model of the pneumatic engine, the impact of temperature changes was neglected. Thus, continuity equation takes the following form [5]:

$$\dot{G}_D - \dot{G}_W = \frac{1}{RT}\frac{d}{dt}(pV), \tag{4}$$

where:
$\dot{G}_d$ – mass flow rate to the system,
$\dot{G}_w$ – mass flow rate from the system,
R – specific gas constant,
T, p, V – air temperature, pressure and volume.

First law of thermodynamics leads to the equation of system energy conservation [5]:

$$\dot{E}_d dt = d\dot{E}_u + \dot{E}_w dt, \tag{5}$$

where:
$\dot{E}_d$ – flow of energy delivered to the system,
$\dot{E}_w$ – flow of energy taken from the system,
$\dot{E}_u$ – internal energy of the system.

In case of pneumatic actuator, energy delivered to the system (and also taken) depends on the airflow rate [5]:

$$\dot{E} = \dot{G}(u + pv), \tag{6}$$

where:
u – specific internal energy of medium,
v – specific volume.

Finally equation for selected actuator chamber, described by pressure p_{a1}, temperature T_{a1} and volume V_{a1} could by written in the following form:

$$\dot{G}_d c_p T_1 - \dot{G}_w c_p T_{a1} = \frac{p_{a1}V_{a1}}{RT_{a1}}\frac{d(c_v T_{a1})}{dt} + c_v T_{a1}\frac{d}{dt}\frac{p_{a1}V_{a1}}{RT_{a1}} + p_{a1}\frac{dV_{a1}}{dt}, \tag{7}$$

moreover, after simplification, knowing volume changes, pressure can be calculated from following differential equation:

$$\frac{dp_{a1}}{dt} = \frac{c_p R}{c_v V_{a1}}\left(\dot{G}_d T_1 - \dot{G}_w c_p - \frac{p_{a1}}{R}\frac{dV_{a1}}{dt}\right), \tag{8}$$

where:
c_p – specific heat for a constant pressure,
c_v – specific heat for a constant volume.

Mass flow of the air delivered to, as well as, taken from the cylinder's chamber, depends on the control valves operation and could by expressed as a product of the flow area, air velocity and its density:

$$\dot{G} = \chi\varphi A v \rho, \tag{9}$$

where:
χ – coefficient,
φ – velocity coefficient,
A – flow area,
v – air flow velocity,
ρ – density of air.

The airflow velocity depends on supply pressure p_s and valve output pressure p_a ratio β:

$$\beta = \frac{p_a}{p_s}, \tag{10}$$

and could be calculated using the next relationships:

$$v = \begin{cases} (0.53)^{\frac{1}{n}} * \sqrt{\frac{2nRT_s}{n-1}\left(1-(0.53)^{\frac{n-1}{n}}\right)} \; for\; \beta \leq 0.53, \\ \\ \left(\frac{p_a}{p_s}\right)^{\frac{1}{n}} * \sqrt{\frac{2nRT_s}{n-1}\left(1-\left(\frac{p_a}{p_s}\right)^{\frac{n-1}{n}}\right)} \; for\; \beta > 0.53, \end{cases} \tag{11}$$

where n – polytrophic exponent.

Elaborated mathematical model was used to build the simulation model of pneumatic engine, and perform calculations to select designed engines and vehicles parameters.

3. Model estimation – test stand

To estimate and verify mathematical model the prototype of pneumatic engine has been designed and built for perform laboratory tests on especially dedicated stand (Fig. 2).

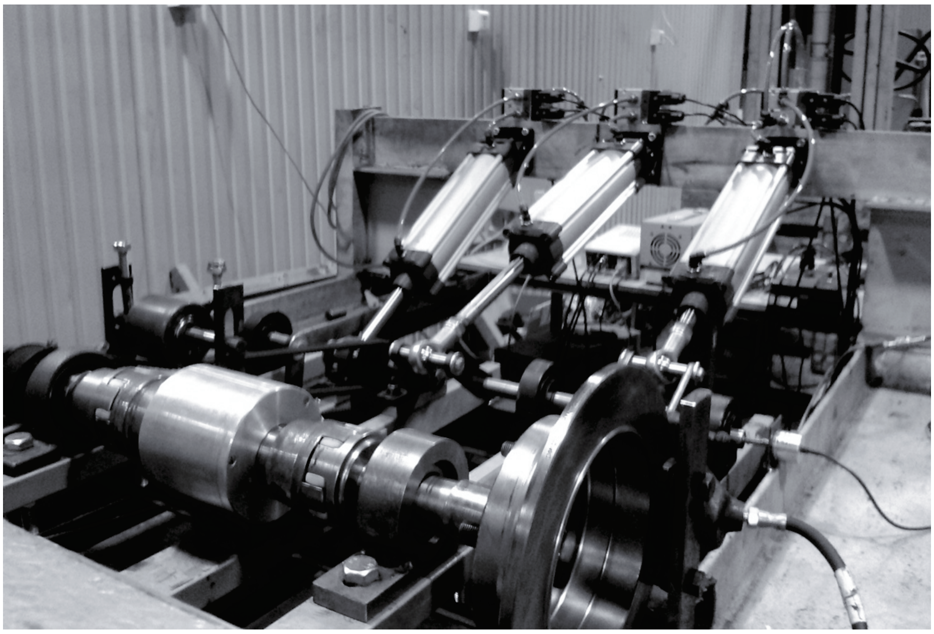

Fig. 2. Pneumatic motor installed on the test stand

In the prototype construction, three typical pneumatic cylinders, with 80 mm of piston diameter were used. Actuators operation was controlled by set of electro-pneumatic distribution valves supplied from compressed air source. To load the engine typical disc brake was mounted. In order to measure and record engine operation parameters, measuring system were used, whose main elements are absolute encoder, pressure and torque sensors, data acquisition board. Block diagram of test stand with prototype pneumatic engine is presented in Fig. 3.

The results of measurements, carried out on a laboratory stand, enabled the determination and selection of significant factors and characteristics of the simulation model. Fig. 3 shows comparison of rotational velocity and pressure in cylinder chambers, achieved in experiment and simulation. Visible differences in the time of the cylinder working chambers filling (pressure built up), leads to correction of coefficients of the air flow resistance through the control valves. In similar way, dry friction force was estimated.

Further experimental studies made it possible to determine the characteristics of torque and engine power in relation to rotational velocity and for different supply. Exemplary plots of pneumatic motor torque, speed and pressure are presented in Fig. 4.

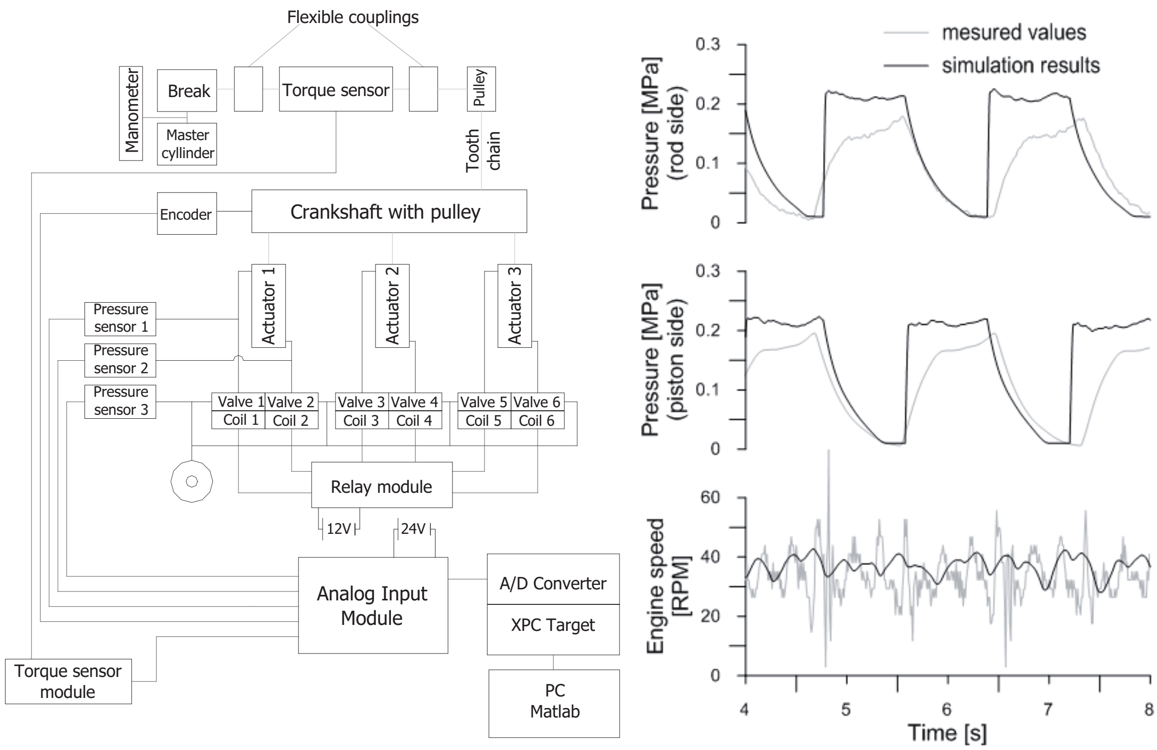

Fig. 3. *Scheme of the test stand with pneumatic engine and results comparison of simulation and measured system main operation values*

For the constructed prototype of pneumatic motor, linear characteristic of torque in a function of rotational speed were obtained. Its lower value than expected is due to high value of flow resistance, of which, it was concluded on the need to increase the pneumatic lines diameter. The consequence of linear torque characteristic is parabolic power dependence of engine speed, with maximum for about 30 rpm. It should be pointed that tested pneumatic engine is low-speed low power motor.

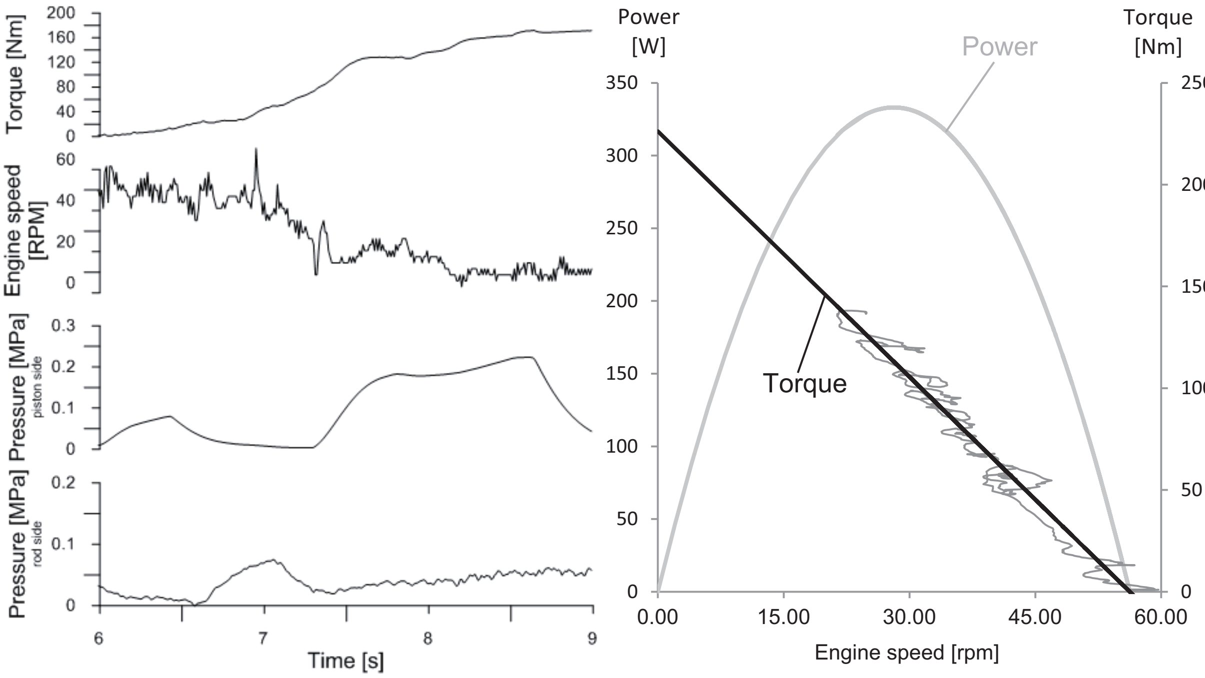

Fig. 4. Characteristics of pneumatic engine (for supply pressure: p_s = 2.5 bar)

Very important aspect of such engine operation is appropriate pneumatic valve control in relation to crankshaft angular position. On the test stand, this function was realized by real time operated computer. It gives high flexibility to implement and test different control algorithms. Particularly, taking into consideration the time of filling and emptying of the cylinders working chambers, control algorithm takes into account the angular offset between the switching of the control valves and the position of the turning shaft (angle of advance) and a dead zone in respect of which the individual cylinders are not supplied. Exemplary characteristics of engine power as a function of angle of advance for different angle without supply is shown in Fig. 5. It could be found that maximum of the power is achieved when the distribution valve opening is about 20^o before dead centre. At the same time, it should be concluded that increasing the width of the dead zone from 0 to about 20^o causes a slight changes in power, while further increase results in a decrease of power, which can be used for controlling the motor.

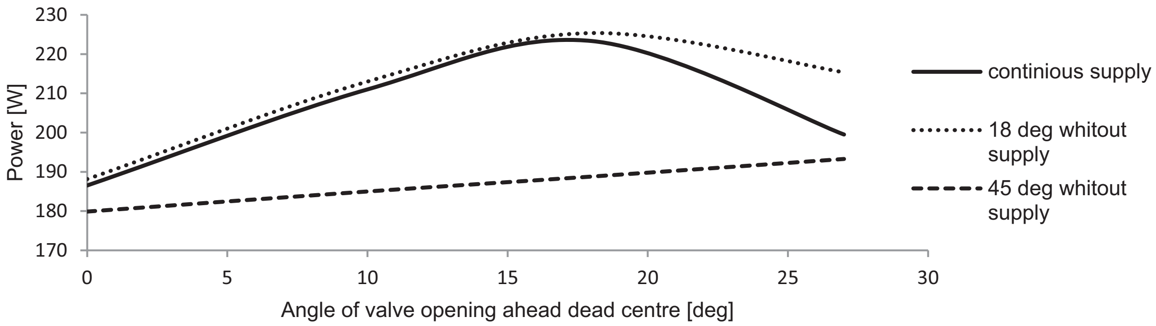

Fig. 5. Influence of control parameters on the power of the engine (for supply pressure: p_s = 3 bar)

4. Simulation of simple light vehicle

After the development and parameterization of a simulation model of the pneumatic engine, it was allowed to go to the selection of its design parameters, such as cylinder's diameters, crank system dimensions and the mechanical gear ratio. As the design assumptions, light vehicle (pneumobil) drive requirements were adopted. For this purpose, a simply model of vehicle was build, based on equation of movement reduced to engine crankshaft [1]. It was assumed that the car would move on flat, bitumen surface:

$$J_{zr}\frac{d\omega}{dt} = M_n - \frac{F_r * D_k}{2 * i_c} - \frac{F_d * D_k}{2 * i_c}, \tag{12}$$

where:
M_N – engine torque,
F_r – rolling resistance,
F_{ad} – air resistance,
D_o – diameter of vehicle wheel,
i_{ce} – mechanical gear ratio.

To specify configuration of the engine, series of simulation were performed using Mat lab Simulink software. Exemplary results of simulation for vehicle acceleration on a distance of 220 m are presented in Fig. 6.

Because the pneumatic engine is low-speed and high torque motor, it is preferred to apply mechanical gearbox, which let to increase vehicle velocity and also its range, achieved from compressed air container. As a result of the simulations, three cylinders with piston diameter of 63 mm were selected. In table 1, the influence of other design parameters such as gear ratio, crank and connecting rod length, on pneumatic vehicle properties are listed. As the parameters characterizing the features of the drive was adopted: speed obtained after run over 220 meters from start (v_{220m}), maximum velocity (v_{max}) and range obtained at a speed of 15 km/h while supplying from typical 10 litters compressed air container (with initial pressure 20 MPa).

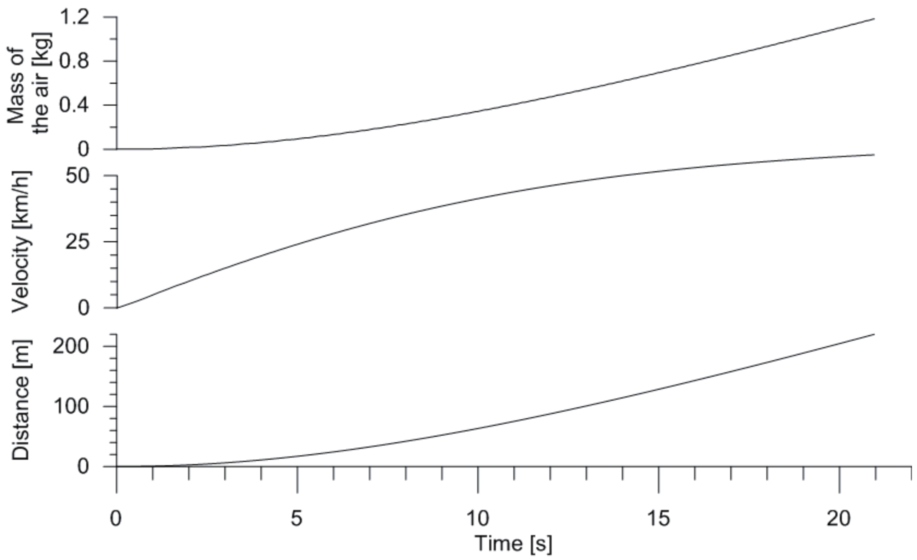

Fig. 6. Simulation of acceleration on distance 220 meters – for: piston diameter 63 mm, rod diameter 20 mm, stroke 170 mm, crank 80 mm, total ratio 0.25

Tab. 1. The influence of gear ratio, and crank length on pneumatic vehicle properties

r	80				90				100			
L	170				190				210			
i	0.1	0.15	0.2	0.25	0.1	0.15	0.2	0.25	0.1	0.15	0.2	0.25
v_{220m} [km/h]	35.5	43.3	48	50.5	38.5	46.5	51.4	54	41.5	49.5	51	56.6
v_{max} [km/h]	61	65	65	63	65	68	68	65	68	71	51.5	66
$range_{15km/h}$ [m]	3391	2742	2075	1686	3311	2599	2052	1579	3193	2471	832	1528

To combine good vehicle acceleration (described by v_{220m} parameter) with long range, it is necessary to use transmission with two drive ratios: 0.1 and 0.25. Then for 80 mm long crank and connecting-rod of 170 mm, pneumatic vehicle will reach over 50 km/h at distance 220 m, and range (with speed 15 km/h) about 3.5 km.

5. Summary

Simulation analysis confirmed by experimental test of the designed pneumatic engine allows concluding that it can be used to drive vehicles and mobile machines. It reaches maximum of torque at low rotational speed of crankshaft. Its mechanical efficiency is very high. Elaborated simulation model of pneumatic engine could be used to determine parameters of designed application. Additionally performed experimental researches showed, that changing of control system settings could improve engine parameters. For that purpose it is recommended to elaborate control algorithm, which can adjust valves timing.

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