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METHOD AND DEVICE FOR INCREASING WEIGHT CHARGING OF FOUR-STROKE ENGINE CYLINDERS

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МЕТОД І ПРИСТРІЙ ПІДВИЩЕННЯ ВАГОВОГО НАПОВНЕННЯ ЦИЛІНДРІВ ЧОТИРИТАКТНИХ ДВИГУНІВ

Purpose. Determination of the possibility of infinitely variable control of the angle of closure delay of the inlet valve of a four-cycle internal combustion engine at a fired engine in order to improve the cylinder weight charging by means of the method of infinite variation of the camshaft angular rate at the end of the intake phase.

Methodology. An analytical model of determination of the law of instantaneous reduction ratio $j_{(\varphi 2)}$ is worked out and it is proposed to rotate the inlet valve shaft unevenly, changing unevenness consecutively and infinitely. Unevenness degree is varied by shift of phases of two identical periodical laws of uneven rotation.

Findings. A curve explaining the character of variation of reduction ratios between the camshaft and the crankshaft of the four-cycle four-cylinder engine is obtained. Along the crankshaft rotation angle there are regular intervals of the moments of the start of fuel mixture or air feed into the cylinder. Curves $\omega^{max}{}_{(\varphi 2)}$, $\omega^{I}{}_{(\varphi 2)}$, $\omega^{II}{}_{(\varphi 2)}$ are shown; they explain the degree of variation of angular rate of the camshaft (inlet valve drive shaft) for the maximum operating mode of the internal combustion engine (ω_2^{max}) and two high-speed modes (ω_2^{I} and ω_2^{II}) at reduced values of rotation frequencies of its shaft ($\omega_2^{max} > \omega_2^{I}$). Unevenness of the analyzed rotation of the camshaft is increased when the engine crankshaft turns decrease, or it may remain unchanged. It is proposed to use a planetary-lever controlled drive for the camshaft drive and the drive kinematic scheme is presented.

Originality. A method for improvement of the engine cylinder weight charging due to infinite variation of the camshaft angular rate at the end of the intake phase and infinite control of angular rotation rate (of the camshaft) of the inlet valve drive shaft is worked out; a kinematic scheme of a double planetary-lever drive is proposed

Practical value. Implementation of the proposed method and device of control of inlet valve closure delay angle in internal combustion engines, and the worked out method for control of the angle rate of the inlet valve drive shaft enables infinite control depending on the fired engine operating mode. It also allows provision of optimum angle of inlet valve closure delay during the intake phase and improvement of weight charging of the cylinders with fuel mixture or air at medium and low frequencies of the engine speed range.

Keywords: *four-cycle engine, camshaft, cylinder weight charging, intake phase, inlet valve*

Introduction. Real load of modern automobile engines is rather low under operating conditions. The share of low-load modes and idle running, as stated in [1], reaches 50 % and more. As these modes are characterized by high fuel expenditure and deterioration of ecological qualities, further improvement of operational, economic and ecological performance of low-load modes presents topical problems of modern engine industry. Incomplete load of a passenger bus engine is confirmed by traffic density research described in [2]. Paper [3] shows that diesel operation fuel efficiency is mainly determined by the economy of low-load and idle running modes. The share of such modes in the whole motor potential is significant. So, the load factors of automobile and tractor diesels are 0.6–0.5, and for locomotive diesels they reach 0.3–0.2. The importance of these modes is confirmed by the fact that in European driving cycle, typical of transport operation in contemporary megapolises, the share of such modes makes 30 %. Increased specific fuel consumption in such modes reduces the efficiency of productive work, raises the cost of transport.

Systems of gas distribution phases change depending on the manufacturer, analyzed in [4], work according to the principle of the change of angle position, but they have similar parameters of regulation of gas distribution phases. For example, BMW VANOS and DOUBLEVANOS allow changing the phases of only inlet or both camshafts, respectively. The mechanism action principle is based on movement of the intermediate part with screw slots transforming the linear movement into camshaft turn-through in relation to the sprocket of the gas distribution chain. Toyota VVT enables smooth changing of gas distribution phases in accordance with conditions of engine operation. As to its structure, the mechanism is similar to a blade pump whose rotor turns in relation to the body under the action of oil pressure force.

Some manufacturers tend to regulate inlet and outlet valves, others only change phases of inlet valves and consider it unprofitable to complicate the design.

The previous experimental research on the process of charging the internal combustion engine cylinders at different frequencies [5] demonstrates that every frequency of crankshaft is to be matched by the most profitable inlet valve closure delay angle at which weight charging of engine cylinders with fuel mixture (air) attains the maximum value. To solve this problem it is expedient to develop a new method of infinite control of angular rotation rate (of the camshaft) of the inlet valve drive shaft and a device.

Analysis of the recent research and publications. Aiming at obtaining high technical, economic and ecological performance of diesel engine 4DTNA2, research described in [5] was performed to improve the processes of mixing, burning, heat transfer, characteristics of gas turbine pressure charging. Improvement of the processes of gas exchange in the diesel engines is of great importance. High quality of processes of emptying and filling cylinders with air mainly depends on the value of flow section of gas distribution elements and time of their opening. Increase in flow sections is usually restricted by the size of the cylinder while the time of opening is determined by gas distribution phases, i.e. moments of opening and closing of inlet and outlet elements (valves). Not only indices of the quality of cylinder emptying and filling but also the value of work required by gas exchange (pumping expenditure) depend on gas distribution phases. Research in [5] aiming at the choice of gas distribution phases of high-speed four-cycle diesel 4DTNA shows that gas distribution phases depend on rotation frequency, the degree of engine forcing, characteristics of gas turbine compressor, conditions (resistance) during the phases of engine inlet and outlet. Hence, the choice of rational phases of gas distribution is a topical and important scientific and engineering problem.

A significant part of experiments and analytical calculations as for researching the process of filling the cylinders of internal combustion gasoline engine with fuel mixture or diesel engine with air, shown in Fig. 1, provide the possibility to make the following observations:

a) at great speeds of the crankshaft the force of inertia of fuel mixture or air motion in the inlet manifold increases sharply. At the same time the pressure in the cylinder at the input phase and at the beginning of compression stroke reduces. Increase in the flow inertia force and decrease in pressure in the cylinder result in growth of additional charge and complete cessation of reverse emission;

b) at medium speeds of the crankshaft the force of inertia of fuel mixture or air flow moving in the inlet manifold increases, input pressure simultaneously decreases, and, consequently, pressure in the cylinder at the beginning of compression stroke also decreases. So, additional charge begins near the bottom dead center, and gradually transforms into reverse emission;

c) at low rotation rates of the engine crankshaft the force of inertia of fuel mixture or air motion is not large. Along with this phenomenon, the input pressure approaches the atmospheric pressure as the speed of mixture or air input into the cylinder is insignificant. As a result, at low speeds of the piston, reverse emission is observed as early as at inlet valve closure delay angle of 20^0 and it increases with the growth of this angle.

Analytical calculations and experiments related to research on the processes of filling the engine cylinders with fuel mixture are described in [3]. The results of calculations and experiments with camshafts and different inlet valve closure delay angles φ_{divc} are shown in Fig. 1.

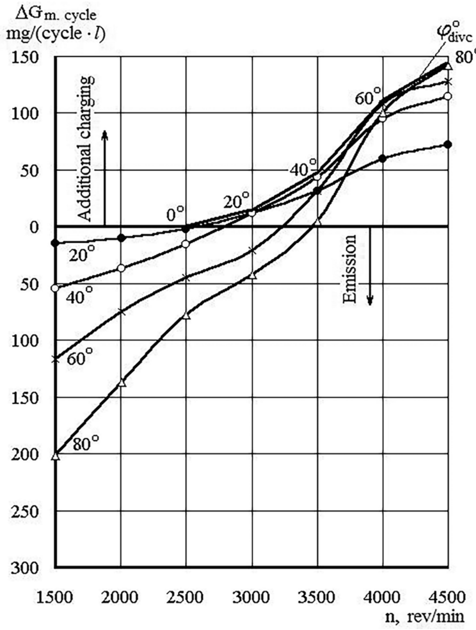

Fig. 1. Graphs of weight charging of the cylinders of internal combustion engine at different angles of inlet valve closure delay

It can be determined from the mentioned research and shown graphs that if the engine crankshaft rotation frequency is lower than the rated value, it is accompanied by analogous decrease in rotation frequency of the camshaft, and motion speed and force of inertia of fuel mixture flow through the inlet hole at the end of input phase during the period of the angle of inlet valve closure delay.

In the zone of medium and low frequencies of the engine high-speed range it results in reduction of additional charging and reverse emission of fuel mixture. So, to solve this problem, a method of infinite control of the angle of inlet valve closure delay is proposed. It will make it possible to increase weight charging of the engine cylinders with fuel mixture. This method is shown by a smooth curve joining the graphs in the upper part of Fig. 1.

To provide increase in weight charging of the cylinders of internal combustion engine in crankshaft medium and low frequency range with fuel mixture or air the authors (A.S. 620643 SSSR, МКИ F 01L 1/12, Patent 2046963 Rossii, МКИ F 01L 1/12) proposed additional devices. Such engineering solutions are original but they contain certain faults preventing their implementation into production.

Objectives of the article. Determination of the possibility of infinite control of angle of four-cycle internal combustion engine inlet valve closure delay with the aim of improvement of weight charging of the cylinders by means of the method of infinite change of angular rate of the camshaft at the end of input phase.

Presentation of the main research and explanation of scientific results. To realize the proposed method it is necessary to transfer rotation from the crankshaft to the inlet valve drive shaft in such a way that instantaneous reduction ratios between the said shafts smoothly change at engine partial modes within every operation cycle in accordance with the established periodic law. In this case the inlet valve drive shaft will rotate unevenly. It will determine optimum values of camshaft angular rate and weight charging of the cylinders at the period of the angle of inlet valve closure delay at the input phase. Shift of phases of uneven rotation periodic laws is performed with this purpose.

The proposed method works in the following way. The inlet valve drive shaft is rotated unevenly according to the determined law of reduction ratio $j_{(\varphi2)}$

$$j_{(\varphi2)} = \omega_{2(\varphi2)}/\omega_1,$$

where φ_2 is the value of the angle of camshaft rotation (the inlet valve drive shaft); ω_1 is the angular rate of the engine crankshaft; ω_2 is the angular rate of the camshaft (the inlet valve drive shaft).

The curve characterizing the change of reduction ratios between the camshaft and the crankshaft of the engine is shown in Fig. 2. As an example, the curve is shown for a four-cycle four-cylinder engine with regular intervals along the angle of crankshaft turn of the moments of start of feeding the fuel mixture or air into the cylinders. Between the crankshaft and the inlet valve drive it is necessary to provide a period of iteration of the law of instantaneous reduction ratios, equal to the minimum period of alternation of time intervals along the angle of rotation between the consequent moments of the start of feeding the fuel mixture or air into the cylinders.

In Figs. 1–4, the following designations are used: Φ_p is the minimum period of change of function $\omega_{2(\varphi2)}$ is the angular rate of rotation of the inlet valve drive shaft; Φ_s is the angle of rotation of the camshaft (inlet valve drive shaft) during the minimum period of alternation of time intervals between consecutive moments of the start of feeding the fuel mixture or air into the cylinders; Φ_{in} is the duration of the phase of input of fuel mixture or air into the cylinder of an internal combustion engine; φ_{poiv} is the angle of preliminary opening of the inlet valve; φ_{mi} – duration of the main input; φ_{divc} is the angle of delay of inlet valve closure.

Durations φ_{divc} of the angle of delay of inlet valve closure at the phase of input of the fuel mixture or air into the cylinders of multi-cylinder internal combustion engines correspond to the cross-hatched area in the Figure. Adjacent areas in these Figures correspond to operation of the valves of different cylinders.

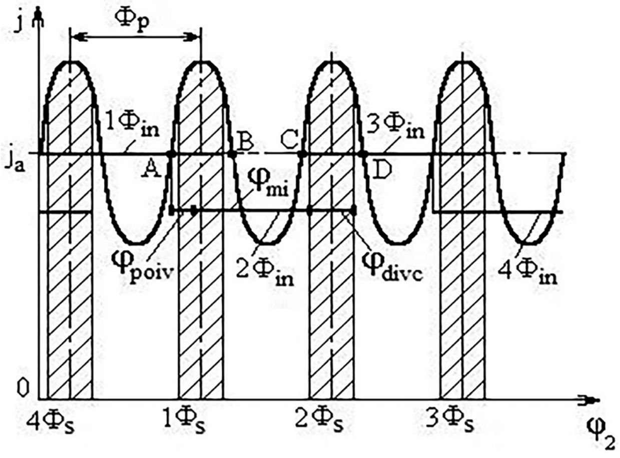

Fig. 2. Realization of the change of reduction ratios for a four-cycle engine with regular alternation of the input phases

The law of change of instantaneous reduction ratio $j_{(\varphi2)}$ is determined identical for all the periods of the input phase at every partial mode of the engine operation. It increases identity of the processes of weight charging of different cylinders of the engine with fuel mixture or air. The value of reduction ratio for the cross-hatched area of the input phase is maintained higher than its average value j_a during the period Φ_p of the change of angular rate $\omega_{2(\varphi2)}$, it provides the required intensification of the process of weight charging of the cylinders within a wide speed range of the internal combustion engine.

Duration of the input phase equals

$$\Phi_{in} = \varphi_{poiv} + \varphi_{mi} + \varphi_{divc}.$$

The number of the periods of oscillations of the camshaft uneven rotation during the whole cycle of the crankshaft can be assigned according to the number of the engine cylinders. As an example, realization of the new method for a four-cycle engine is shown in Fig. 1. If the start of input phase and the start of the assigned oscillations of the camshaft are located at the same point A, the complete period of shaft oscillations will be performed from point A to point C and will belong to the angle $\varphi_{poiv} + \varphi_{mi}$ of the preliminary opening of the inlet valve and main input. Half of the following period of camshaft oscillations from point C to point D corresponds to the inlet valve closure delay angle φ_{divc}. As at this section the angular rate of the camshaft uneven rotation exceeds the average one, value φ_{divc} will reduce.

A periodic curve in Fig. 3 explains the value of change of this reduction ratio.

Curves $\omega^{max}_{(\varphi2)}$, $\omega^{I}_{(\varphi2)}$, $\omega^{II}_{(\varphi2)}$ in Fig. 4 explain the value of change of the angular rate of rotation of the camshaft (the inlet valve drive shaft) for the maximum mode of internal combustion engine operation (ω_2^{max}) and two high-speed modes (ω^{I}_2 and ω^{II}_2) at reduced values of rotation frequencies of its shaft ($\omega_2^{max} > \omega^{I}_2 > \omega^{II}_2$).

In this Figure the straight dotted lines denote average values of the angular rates ω_2.

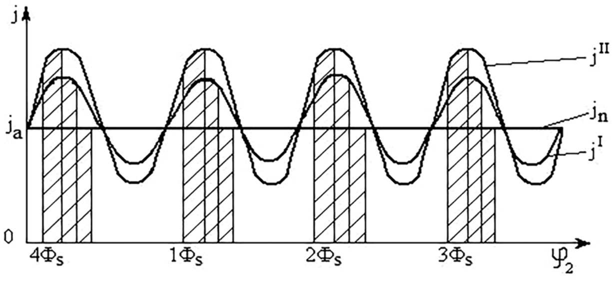

Fig. 3. Value of change of the inlet valve closure delay angle depending on the reduction ratio

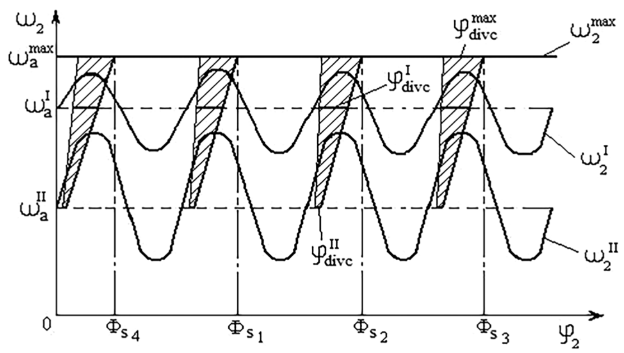

Fig. 4. Value of change of the angular rate of rotation of the camshaft (the inlet valve drive shaft), de-pending on the rotation frequency of the engine crankshaft and corresponding angles of inlet valve closure delay

Fig. 3 shows the laws of reduction ratio $j^{max}{}_{(\varphi2)}, j^{I}{}_{(\varphi2)}, j^{II}{}_{(\varphi2)}$ corresponding to the mentioned angular rates. During realization of this method at maximum modes of operation with high frequency of engine shaft rotation, the inlet valve drive shaft (the camshaft) must be evenly rotated, providing the camshaft with the angular rate ω_2, proportional to the angular rate ω_1 of the crankshaft

$$\omega_2 = j_a\,\omega_1,$$

and at partial modes the camshaft must be rotated unevenly

$$\omega_2 = j_{(\varphi2)}\,\omega_1.$$

Unevenness of the considered rotation of the camshaft at reduction of rotations of the engine crankshaft increases or may remain unchanged.

To realize the described method of control it is proposed to use a camshaft planetary-lever controlled drive. A schematic kinetic diagram of the device is shown in Fig. 5.

A planetary-lever-actuated clutch (PLC) is installed in the drive of the engine camshaft and is intended for the change of the angular rate of rotation of the camshaft (inlet valve drive shaft) depending on the speed mode of engine operation. The planetary-lever-actuated clutch has a simple construction arrangement and high reliability. It performs the functions of infinite change of maximum reduction ratio j_{max} optimal in the range from 1 to 2.5–3. Value j_{max} can be regulated manually (to provide the regulating intensity of the input during bench test of the engine) or by means of an ad hoc automatic regulator, or by a throttle plate from the control lever at a fired engine.

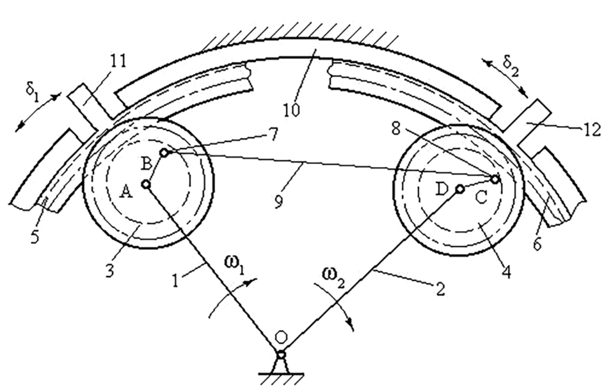

Fig. 5. A schematic kinetic diagram of the planetary-lever drive

A planetary-lever-actuated clutch (PLC) consists of two planetary mechanisms without sun gears. On the driving spider *1* of the first planetary mechanism and the driven spider *2* of the second planetary mechanism satellites *3* and *4* are installed in the holes, the satellites are geared with crown gears *5* and *6*, located in parallel surfaces coaxially with each other. On satellites *3* and *4* at equal distances from their rotation axes hinged joints *7* and *8* are installed, they form cranks in relation to the axis of satellites rotation and are connected with each other by rigid rod *9*. Crown gears with internal girth gear are installed in sockets of stationary body *10* and have locks *11* and *12* preventing turning-through. The angle of rotation of the crown gears is changed by manual or automatic regulation of value j_{max}. The character of movement of the driven spider and links of the hinge-lever chain ABCD is determined by value δ of relative angular shift of the crown gears. At certain position of locks *11* and *12* (corresponding to values $\delta = 0$) of the output (I) and all the following (II, III, etc.) configurations of the chain ABCD will make parallelograms (Fig. 6, *a*), and spider *2* will move synchronously with spider *1*, i.e. here $\omega_2 = \omega_1$, $j_{max} = 1$ rotation will be performed evenly.

After rotation of gears *5* and *6* the initial configuration will be distorted and take the form shown in Fig. 6, *b*. In this case, when spider *1* rotates, spider *2* will catch up with it at some sections, and fall behind at other sections, i.e. it will rotate unevenly.

The period of change of the angular rate ω_2 of the driven spider (camshaft) is determined by reduction ratio i_k of the gear transmission satellite – crown gear (when the spider is stationary), i.e. by relation of corresponding reference diameters D_{kk} and d_c, according to formula

$$\Delta\Phi = 360^{\circ}/i_k.$$

It follows from this formula that for a two-cylinder engine the diameter of the crown gear is to be twice as big as the diameter of the satellite, for a four-cylinder engine it must be four times as big, etc.

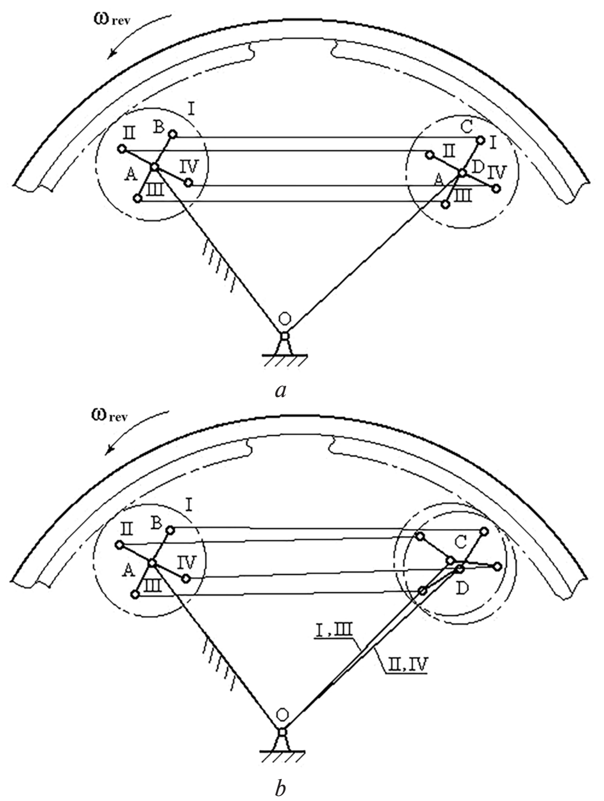

Fig. 6. Scheme of location of PLC hinge-lever chain links:
a – δ = 0; b – δ ≠ 0

Period $\Delta\Phi_\delta$ of the change of the regulating angle δ is also $\Delta\Phi$. Fig. 7 explains this determination.

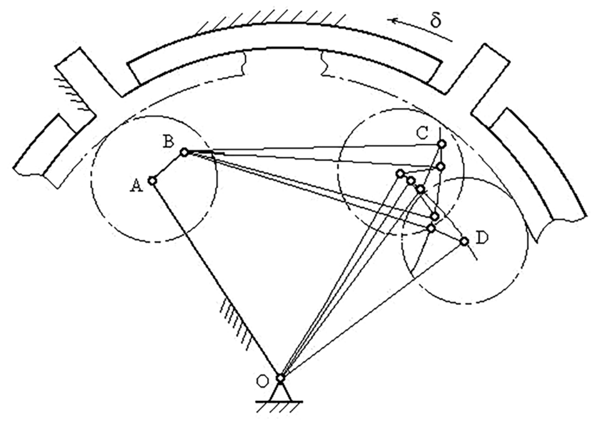

Fig. 7. Scheme of location of the links of the hinge-lever chain of the planetary-lever clutch during in-crease of δ from 0 to Φ

Change of the ABCD chain configuration with increasing δ from *0* to *Φ* is shown here (turn of crown gear *6* at stationary crown gear *5*, Fig. *5*). The latter configuration coincides with the initial one, so $\Delta\Phi_\delta = \Delta\Phi$. However, at values $\delta \geq \Delta\Phi/2$ reduction ratio starts to reduce (at $\delta = \Delta\Phi$, $j_{max} = 1$), so this part of the range of angles δ is not used during PLC operation.

The analyzed PLC has a simple kinematic scheme and is an integrated mechanism in which the law of reduction ratio depends on the choice of a small number of structural parameters. In fact, at the assigned it only depends on two structural parameters

$$x_1 = e = |AB| / |AO|;$$
$$x_2 = e = |BC| / |AO|,$$

and two regulating angles δ_1 and δ_2 of rotation of crown gears.

Conclusions. Application of the proposed method and device for control of the angular rate of rotation of camshaft (inlet valve drive shaft) in four-cycle internal combustion engines provides the possibility: to perform infinite control of the angle of inlet valve closure delay at a fired engine; to provide optimum weight charging of the cylinders with fuel mixture or air depending on the operation mode of the four-cycle engine. The following stage of this work consists in development of methods for kinematic calculations of rational parameters of camshaft planetary-lever controlled drive.

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Мета. Винайдення можливості на працюючому двигуні безступінчастого керування кутом запізнення закриття впускного клапана чотиритактного двигуна внутрішнього згоряння для підвищення вагового наповнення циліндрів за рахунок методу безступінчастої зміни кутової швидкості розподільчого вала в кінці фази впуску.

Методика. Розроблена аналітична модель визначення закону миттєвого передавального відношення $j_{(\varphi 2)}$ і запропоновано вал приводу впускного клапана обертати нерівномірно, змінюючи нерівномірність послідовно безступінчасто. Зміну величини нерівномірності здійснюють зсувом фаз двох ідентичних періодичних законів нерівномірного обертання.

Результати. Наведено криву лінію, що пояснює характер зміни передавальних відношень між розподільчим валом і колінчастим валом чотиритак-

тного чотирициліндрового двигуна, з рівномірними проміжками по куту повороту колінчастого вала моментів початку подачі горючої суміші або повітря в циліндри. Показані криві $\omega^{max}{}_{(\varphi 2)}$, $\omega^{I}{}_{(\varphi 2)}$, $\omega^{II}{}_{(\varphi 2)}$, що пояснюють величину зміни кутової швидкості обертання розподільчого вала (вала приводу впускного клапана) для максимального режиму роботи двигуна внутрішнього згоряння (ω_2^{max}) і двох швидкісних режимів (ω_2^{I} и ω_2^{I}) на знижених значеннях частот обертання його вала ($\omega_2^{max} > \omega_2^{I}$).

Нерівномірність розглянутого обертання розподільчого вала при зменшенні обертів колінчастого вала двигуна збільшується або може залишатися незмінною. Запропоновано використовувати для привода розподільчого вала планетарно-важільний керований привод, наведена кінематична схема привода.

Наукова новизна. Розроблено метод підвищення вагового наповнення циліндрів двигуна за рахунок безступінчастої зміни кутової швидкості розподільчого вала в кінці фази впуску й безступінчастого керування кутовою швидкістю обертання вала привода впускного клапана, запропонована кінематична схема здвоєного планетарно-важільного привода.

Практична значимість. Впровадження на двигунах внутрішнього згоряння способу й пристрою керування кутом запізнення закриття впускного клапана та розробленим методом управління кутовою швидкістю обертання вала привода впускного клапана дає можливість здійснити безступінчасте управління залежно від режиму роботи на працюючому двигуні. А у фазі впуску забезпечити оптимальний кут запізнення закриття впускного клапана й підвищити вагове наповнення циліндрів горючою сумішшю або повітрям на середніх і нижніх частотах швидкісного діапазону двигуна.

Ключові слова: *чотиритактний двигун, розподільчий вал, вагове наповнення циліндрів, фаза впуску, впускний клапан*

Цель. Найти возможность на работающем двигателе бесступенчато управлять углом запаздывания закрытия впускного клапана четырехтактного двигателя внутреннего сгорания для повышения весового наполнения цилиндров методом бесступенчатого изменения угловой скорости распредвала в конце фазы впуска.

Методика. Разработана аналитическая модель определения закона мгновенного передаточного отношения $j_{(\varphi 2)}$ и предложено вал привода впускного клапана вращать неравномерно, изменяя неравномерность последовательно, бесступенчато. Изменение величины неравномерности осуществляют сдвигом фаз двух идентичных периодических законов неравномерного вращения.

Результаты. Приведена кривая линия, которая объясняет характер изменения передаточных отношений между распредвалом и коленчатым валом четырехтактного четырехцилиндрового двигателя, с равномерными промежутками по углу поворота коленчатого вала моментов начала подачи горючей смеси или воздуха в цилиндры. Показаны кривые $\omega^{max}{}_{(\varphi 2)}$, $\omega^{I}{}_{(\varphi 2)}$, $\omega^{II}{}_{(\varphi 2)}$, которые объясняют величину изменения угловой скорости распредвала (вала привода впускного клапана) для максимального режима работы двигателя внутреннего сгорания (ω_2^{max}) и двух скоростных режимов (ω_2^{I} и ω_2^{I}) на сниженных значениях частот вращения его вала ($\omega_2^{max} > \omega_2^{I}$).

Неравномерность рассмотренного вращения распредвала при уменьшении оборотов коленчатого вала двигателя увеличивается или может оставаться неизменной. Предложено использовать для привода распредвала планетарно-рычажный управляемый привод, приведена кинематическая схема привода.

Научная новизна. Разработан метод повышения весового наполнения цилиндров двигателя за счет бесступенчатого изменения угловой скорости распредвала в конце фазы впуска и бесступенчатого управления угловой скоростью вращения вала привода впускного клапана, предложена кинематическая схема сдвоенного планетарно-рычажного привода.

Практическая значимость. Применение на двигателях внутреннего сгорания способа и устройства управления углом запаздывания закрытия впускного клапана и разработанным методом управления угловой скоростью вращения вала привода впускного клапана дает возможность осуществить бесступенчатое управление в зависимости от режима работы на работающем двигателе. А в фазе впуска обеспечить оптимальный угол запаздывания закрытия впускного клапана и повысить весовое наполнение цилиндров горючей смесью или воздухом на средних и нижних частотах скоростного диапазона двигателя.

Ключевые слова: *четырехтактный двигатель, распределительный вал, весовое наполнение цилиндров, фаза впуска, впускной клапан*

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