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DESIGNING PASSENGER VEHICLE DIESEL ENGINE CAMS WITH ENHANCED DYNAMIC CHARACTERISTICS

Purpose. Automating the design of working profiles for cam mechanisms in heavy-, medium- and light-duty internal combustion engines with enhanced dynamic characteristics.

Methodology. By applying discrete differentiation to the tabulated law of tappet displacement, non-oscillatory graphs for velocity and acceleration were obtained. These graphs served as the basis for determining the polar coordinates of the cam profile. The SolidWorks CAD system was employed to generate a 3D computer model of the camshaft with enhanced dynamic characteristics.

Findings. Tuning camshafts ensure the optimum supply of a full charge of the mixture to the cylinder by increasing the height and speed of valve lift. A notable characteristic of these camshafts is their ability to extend the threshold of detonation at lower crankshaft speeds. The cam profiles of these camshafts are characterised by exceptional smoothness, ensuring reliable operation of the valve timing mechanism. The performed calculations show that the tuning cam profile has a greater radius of curvature at the cam-tappet contact point compared to the conventional profile. This provides more favourable conditions for hydrodynamic oil wedge formation between the contact surfaces due to an increase in the hydrodynamic effective velocity.

Originality. Implementing a novel approach to camshaft design enabled the creation of tuning camshafts, ensuring optimal cylinder filling by maximising valve lift height and speed. A key original feature is their capacity to raise the detonation limit at lower RPMs, complemented by exceptionally smooth profiles that contribute to reliable valve timing.

Practical value. A universal methodology for profiling the functional surfaces of tuning camshafts intended for heavy-, medium- and light-duty engines has been developed, ensuring their operational reliability and durability.

Keywords: *internal combustion engine, tuning camshaft, cam, valve timing mechanism*

Introduction. Performance-tuned vehicles typically have more powerful engines than standard production vehicles. This is due to the fact that the actual power output of the latter is always lower than the theoretical design power due to efficiency losses caused by thermal and mechanical factors, including assembly quality.

There are several ways to enhance the power output of a passenger vehicle diesel engine. This can be done by installing advanced engine control systems, modifying the displacement, redesigning the cylinder head, optimising the valve timing, as well as improving the intake/exhaust systems, and fuel supply.

Engine power enhancement fundamentally depends on three key factors: engine torque, rotational speed and losses (efficiency). Engine torque is determined by the combustion gas pressure acting on the piston and the crank radius of the crankshaft. This means that power can be increased by using a crankshaft with a larger crank radius and/or increasing the pressure of the combustion gases on the piston, or the piston diameter. Engine displacement can be enhanced by 10–15 %, (reaching a maximum of 30 %) through three primary methods: by replacing the standard crankshaft with a long-stroke one, replacing pistons and boring out cylinders (including cylinder sleeving), or combining both crankshaft replacement and piston upgrades. The power output increases proportionally within these parameters.

The engine rotational speed is influenced by the valve timing characteristics and the rotating assembly mass of the engine. To increase the revolutions per minute (RPM), camshafts with increased phases (over 320°) and an increased valve lift (up to 11 mm or greater) are installed. In addition, upgraded rocker arms and high-tension valve springs are used. A precise timing adjustment is fulfilled by installing adjustable split camshaft sprockets. All replacement components must be lightweight and durable, which is achieved by using premium materials.

The research presented in the paper concerns the tuning of a diesel internal combustion engine by increasing revolutions due to a change in the design of the camshaft.

Camshaft designs vary significantly based on their application. Low-range torque camshafts are specifically designed for urban driving conditions. Universal camshafts serve both urban and high-speed road use, while high-range camshafts are intended for competitive racing.

The most commonly used vehicles are those equipped with engines featuring universal camshafts. These vehicles must provide adequate responsiveness when accelerating from a standstill while simultaneously delivering sufficient power for high-speed driving.

To improve vehicle performance at low speeds, it is necessary to quickly supply the cylinder with the required charge of the working mixture. For this purpose, one needs to increase the rate at which exhaust gases are expelled from the combustion chamber and the supply of a fresh portion of fuel mixture; that is, to shorten the opening phases of both intake and exhaust valves.

The reliability of an internal combustion engine also depends on adequate lubrication of its moving parts. The lubrication system is designed to ensure the continuous supply of lubricants to the bearings and to directly address the following tasks:

- reducing friction between interacting components. The system's elements aim to minimise all types of friction – boundary (direct contact between surfaces), hydrodynamic (with a complete lubricant film separating surfaces), and mixed (where partial surface contact occurs). Pure boundary friction is uncommon in normal operation and typically occurs during component deformation (e.g., in bearings) or when lubricant films fail in extreme pressure conditions. Hydrodynamic friction predominates in situations like high-speed rotation, where oil forms a wedge between a shaft journal and bearing surface;
- heat dissipation and component cooling. This is achieved through coolant circulation, where oil first gets cooled before absorbing heat from engine components;
- removal of wear debris through oil changes (including metal particles, laminar deposits, and contaminants). Fatigue wear from rolling/sliding contact is most prevalent, alongside adhesive, abrasive, and corrosive wear mechanisms;
- prevention of carbon accumulation. Deposits commonly form in direct injection systems (where fuel enters the combustion chamber directly) and in vehicles with irregular use, prolonged idling, or cold operation without proper warm-up;
- corrosion protection. Lubricants inhibit oxidation caused by atmospheric exposure.

To accomplish these objectives, the oil pressure in the engine lubrication system must be sufficiently high. An adequate oil supply is essential to maintain hydrodynamic lubrication and ensure effective heat dissipation from component surfaces.

Tuning camshafts ensure the optimum supply of a full charge of the mixture to the cylinder by increasing the height and speed of valve lift. A notable characteristic of these camshafts is their ability to extend the threshold of detonation at lower crankshaft speeds. The cam profiles of these camshafts are characterised by exceptional smoothness, ensuring reliable operation of the valve train mechanism (VTM). It also reduces fuel consumption and exhaust emissions by 10–15 %, the tendency for detonation and engine heat build-up, and increases engine life.

The reliability of a diesel ICE is also significantly affected by the cam profile design of the camshaft. The cam profile must feature an absolutely smooth contour without sharp transitions between different profile segments. The presence of cylindrical rounding at the top of the cam negatively impacts the entire VTM operation.

This necessitates the development of an advanced cam profile design methodology that enhances the reliability of both the VTM and the overall engine performance.

Literature review. The reliable and efficient gas exchange process in passenger vehicle diesel engines depends on a number of structural and operational factors. Among the key optimizable parameters of the gas exchange system are the aerodynamic characteristics of the intake and exhaust systems, as well as the valve timing parameters.

To improve diesel engine performance, enhancing optimisation algorithms remains a primary requirement. However, existing optimisation approaches encounter several difficulties that limit their effectiveness. These include noisy experimental conditions, stability issues, inaccuracies and temporal variations in fitness model approximations, as noted in reference [1].

The study presented in [2] introduces a methodology for improving heavy-duty split-cycle regenerative engines through piston design modifications. This approach incorporates a strategy for rapid and cost-effective adjustment of the compression/expansion ratio, advanced materials and technologies for reducing thermal losses, and thermal expansion analysis to guide material selection for both piston construction and thermal barrier coatings to optimise piston functionality. However, the proposed methodology focuses specifically on particular engine components instead of offering a comprehensive solution for the entire engine system.

Knowing fuel injection speed is also crucial for advancing injection systems, improving engine performance, and controlling emissions. Modelling fuel injection speed based on experimental data can significantly contribute to studying injection behaviour across the entire engine operating range. Furthermore, injection speed modelling can substantially reduce the amount of experimental data required for such investigations [3]. However, these studies primarily focus on enhancing the accuracy of measurement and modelling of fuel injection speed in gasoline ICEs.

The split-cycle regenerative engine represents a fundamentally new class of ICEs, offering a step-change improvement in thermal efficiency compared to conventional Otto and Diesel cycle engines [4]. In this innovative design, the compression and combustion strokes occur in separate cylinders. The system achieves exceptional efficiency through intensive cooling of the compression stroke via direct liquid nitrogen injection into the chamber, enabling effective heat recovery between the compression and combustion cylinders. Reported performance metrics demonstrate brake thermal efficiencies exceeding 50 % without compression cooling, reaching 60 % when employing liquid nitrogen injection during the compression stroke. However, this technology currently targets the long-haul heavy-duty transportation sector, where electrification is inefficient.

The basis of the effective operation of the internal combustion diesel engine is the valve train mechanism. The main part of the VTM is the camshaft, which controls the opening and closing of the engine valves.

One of the primary causes of diesel engine failure is incorrect valve timing. This issue is particularly critical for engines equipped with modular camshafts.

Reference [5] considers methods of quality assessment for composite camshafts assembled using pulsating hydroforming.

This technology is relatively new in comparison with rolling, forging or stamping, so product and process developers have limited knowledge about it. Compared to traditional production, in particular by stamping and welding, pipe hydroforming offers several advantages, such as 1) reducing the cost of the workpiece, the cost of the tool and the weight of the product; 2) improving structural stability and increasing the strength and stiffness of the moulded parts; 3) more uniform thickness distribution; 4) reduced secondary operations, etc. However, this technology has some drawbacks, such as slow cycle times, expensive equipment, and the lack of an effective database for tool and process design.

When analysing diesel engine accidents, one of the causes of camshaft failure was identified. This is the erosion of the shaft's working surfaces due to insufficient lubrication. In addition to lubrication, an effective alternative for protecting camshaft surfaces from cavitation erosion is the application of composite coatings made of wear-resistant materials [6–8]. The addition of metal particles improves the resistance of the composite coating to cavitation due to the lower porosity formed in the coatings. However, to a certain extent, the low adhesion of the particles can counteract the positive effect of low porosity, resulting in a reduced resistance to cavitation erosion. In addition, the mechanical properties of composites are not easy to predict due to the nonlinear nature of the relationship between them and the primary material of the product.

References [9, 10] contain the results of an investigation into the causes of failure of such camshafts. The analysis was based on the finite element method using Solidworks and ANSYS 17.0 software. The experiment showed that the camshaft failure occurred due to an excessive temperature difference in the transition zones. This difference leads to a reduction in the load capacity of the camshaft, as well as the formation and propagation of cracks.

Experiments involving orthogonal torsion and laser measurements have identified the main causes of failure in assembled camshafts.

It is important to consider that the functional surfaces of the tappet and cam are also subjected to cyclic impact loads, cyclic bending and torsion. This often leads to premature wear of the cam profile, affecting camshaft speed, valve movement and torque. Furthermore, when stresses are concentrated, fatigue fractures of the camshaft can occur.

From the above, it can be concluded that in addition to wear resistance, the camshaft must possess sufficient impact toughness [11].

The lubrication of the cam/tappet joint and the quality of the functional surfaces of the cam and tappet play a significant role in the reliability of camshaft operation. Failure to meet these requirements leads to unstable engine operation or camshaft failure.

Similar requirements for operational reliability and manufacturing accuracy are made for other mechanisms. For example, for rotor-planetary hydraulic machines. In references [12, 13], the effects of manufacturing accuracy of rotor functional surfaces on the reliability of positive displacement hydraulic machines are considered.

The authors investigated the relationship between the location of contact points on hydraulic motor rotor profiles and methods for controlling the shape imperfections of the inner and outer hydraulic motor rotors.

In the development of low-speed hydraulic motors, where the working elements must operate at low rotational speeds while generating high torque, a critical issue arises from form deviations in the rotor and distribution systems. These inaccuracies induce fluid flow pulsation [14]. This problem can be determined and eliminated by adjusting the gaps between the rotors and the stator.

Similarly, the clearances between the cam and tappet working surfaces in an engine can be determined. The clearance limit value can act as a normalised performance criterion for an ICE. However, chaotic cyclic fluctuations of cam shape imperfections affect the value of the maximum allowable clearance, which in turn affects the reliability of the VTM.

The stability of the ICE depends on the reliable and seamless operation of the VTM. This is particularly true of the manufacturing accuracy of the camshaft cams.

The main task of cam profiling is to determine the coordinates of the polar radius ρ_i and the cam rotation angle α_i of its points, depending on the law of tappet displacement. This law determines the displacement of the valve, providing a given opening time and change of the working medium in the engine cylinder. Consequently, the law of tappet displacement is determined by thermodynamic calculation of processes in the ICE cylinder.

Reference [15] investigates the design and development of a valve train system for a split-cycle regenerative diesel engine (SCRE), which imposes unique requirements on valve lift, duration, and phasing compared to a conventional 4-stroke gasoline engine. The authors present the requirements for the camshaft profile, its functions, design, the analysis and test results obtained through an experimental program for a heavy-duty (HD) split-cycle regenerative engine. However, this research specifically focuses on developing specialised diesel engines for commercial freight vehicles.

In a diesel ICE for a passenger vehicle, unlike in a gasoline engine, extremely high system speeds and the non-linear nature of fuel combustion are combined with the unpredictable behaviour of the idle mechanism during engine braking. As a result, there arises a need to develop a new camshaft concept for continuously variable valve timing. In study [16], the use of a camshaft with a variable curved cam surface was proposed. By employing a ball-type contact follower that traces a specific contour, the same volumetric efficiency was achieved as with the individual displacement of a specific cam along the same contour. By providing the camshaft with axial movement and allowing the follower to trace different contours, continuous valve timing variation was achieved. However, this significantly complicates the design of the valve timing mechanism.

A significant improvement in the dynamic characteristics of a diesel ICE can be achieved by increasing the lift of the exhaust valve. This reduces the time required to remove exhaust gases from the combustion chamber and accelerates the filling of the cylinder with a new portion of the fuel mixture. In study [17], the authors conducted an experimental analysis of the effects of maximum valve lift in the tappet-type valve train system for diesel ICEs. Potential problems associated with unwanted vibrations in high-speed engines include tappet bounce and contact surface impacts between valves and seats, which cause collisions within the tappet-type valve train system. The severity of these impacts depends on the valve lift value and the valve closing speed. Large forces and stresses occur during collisions between the cam follower and the tappet. This may lead to premature system failure due to undesirable vibrations.

During diesel engine testing using a special cycle that covers all critical operating zones (including engine braking), the causes of extreme loads were identified. One of these causes is the imperfect geometric profile of the camshaft cam working surface. Due to these optimisation studies and validation processes, the risk of potential critical failure of the valve mechanism and related engine components can be eliminated.

Particular attention must be paid to the issue of obtaining curved cam surfaces of the ICE camshaft that can ensure the required quality of valve opening and closing.

To describe the curved cam surfaces, the use of a rational-quadratic trigonometric interpolation spline [18] was considered, which can effectively construct shape-preserving interpolation curves. The use of B-splines or segments of second-order curves for forming linear elements of planar curves defined analytically or constructively [19] was also considered.

However, the use of continuous functions for designing the working surfaces of cam profiles may lead to surface oscillations. Therefore, it is more appropriate to use discrete point arrays to describe cam surfaces.

Studies [20, 21] consider the design of smooth surface profiles with complex geometric shapes based on point arrays. The framework elements are contours obtained by interpolating sets of points. Algorithms for designing planar and spatial contours were developed. The contour is formed within the area of possible locations of segments of the interpolated curve, along which the curvature values increase or decrease monotonically.

Purpose. The purpose of the article is to develop a universal methodology for designing the working profiles of cam mechanisms of internal combustion engines of heavy-, medium- and light-duty types.

In order to achieve the set purpose, it is necessary to fulfil the following tasks:

- to review the existing methods for designing cam profiles;
- to identify the disadvantages of conventional methods;
- to propose a method for obtaining the cam profile of tuning camshaft of the ICE with enhanced dynamic characteristics.

Methods. One of the most important components in the operation of a car engine is the camshaft, which is part of the VTM. The camshaft controls the intake and exhaust strokes of the engine cycle.

Depending on the engine's design, the VTM may have either overhead or side-mounted valves. Nowadays, overhead valve systems are more common. This configuration simplifies and speeds up maintenance procedures such as camshaft adjustment and repair, which may require spare parts for the camshaft.

From a structural standpoint, the camshaft is linked to the crankshaft, typically via a timing chain or belt. The chain or belt is mounted onto a crankshaft sprocket or a camshaft pulley. A slotted gear-type camshaft pulley is considered one of the most practical and efficient designs and is frequently used in engine tuning to increase performance.

Bearings, in which the camshaft journals rotate, are located on the cylinder head. If the journal mounts become damaged, camshaft repair bushings are used for restoration.

To prevent axial play, the camshaft includes special locking devices in its design. A through-hole runs along the shaft's axis to supply oil to the friction surfaces, and this channel is sealed at the rear with a camshaft plug.

The number of cams on the camshaft corresponds to the number of intake and exhaust valves. The cams perform the key function of controlling the engine's valve timing and the sequence of cylinder operation.

Each valve is actuated by a cam, which presses against a tappet to open the valve. Once the cam moves away from the tappet, a strong return spring ensures the valve closes.

The cams of the camshaft are located between the journal bearings. The valve timing phase, which depends on engine RPM and the design of the intake and exhaust valves, is determined experimentally. These specifications for a particular engine model can be found in technical tables and diagrams provided by the manufacturer.

The design of the cam working surface profile is based on determining the cam rotation angle α_i and its polar radius ρ_i of points, depending on the tappet motion law [22].

The most prevalent method is to tabulate the displacement S of the tappet depending on the cam angle α, assuming that the angular speed ω of the camshaft rotation is constant and non-negative [22].

Let us examine the solution for modelling the cam profile of a diesel engine's VTM. The tappet displacement curve S of the diesel engine forms a discretely presented curve (DPC) symmetric relative to $\alpha = 57°30'$, with a main grid step of $\Delta\alpha = 5°$.

The design of the working surface profile of the cam is based on determining the cam rotation angle α_i and the polar radius ρ_i of its points, depending on the law of tappet displacement [22].

In [22], an algorithm for determining the values of speeds s'_i and accelerations s''_i of the tappet displacement was implemented, and comparison of the results by the conventional and developed methods was carried out.

The graph of the tappet movement was used as a basis for calculations [22].

To obtain the result, the authors constructed a band of differential projections based on the values of the *1st* s'_i and *2nd* s''_i separated differences of the values of the function $S_i(\alpha)$. The values of speeds s'_i and accelerations s''_i within the obtained band of differential projections ensure the absence of oscillation of the solution [22].

Results. The ordinates of the corrected points on the displacement graph of $S_i(\alpha)$ and the corrected values of the *1st* s'_i and *2nd* s''_i derivatives [22] can be used to calculate the coordinates of the cam profile points of the VTM.

The initial data are as follows: φ_i is the cam rotation angle; S_i is distance from the cam axis to the tappet plate; s'_i is tappet speed; s''_i is acceleration of the pusher.

With the analytical definition of the law of tappet displacement, the coordinates x and y of the points of the cam profile are determined by the formulae

$$x = S \cdot \sin\varphi + s' \cos\varphi;$$

$$y = S \cdot \cos\varphi - s' \sin\varphi,$$

or in polar coordinates

$$\rho = \sqrt{S^2 + s'^2};$$

$$\psi = \varphi + \operatorname{arctg}\frac{s'}{S}.$$

Since the camshaft has a rotation axis which is perpendicular to the plane of the cam profile, it is more convenient to calculate the coordinates of the points of the profile in the polar coordinate system. The results of the calculations are shown in Table 1.

Table 1

Polar coordinates of the points of the cam profile

i	φ_i, degrees	ρ_i, mm	ψ_i, degrees
1	0	0.14339	6.242374
2	5	0.36585	22.54024
3	10	1.063872	36.80919
4	15	2.105925	47.79237
5	16.51	2.47901	50.78285
6	20	3.36819	51.73001
7	25	4.50026	52.36308
8	30	5.50078	53.16926
9	35	6.34559	53.83092
10	40	7.02941	54.69706
11	45	7.54724	55.63439
12	50	7.89812	56.32424
13	55	8.06898	57.1705
14	57.5	8.09094	57.5
15	60	8.06898	57.82975
16	65	7.89812	58.67576
17	70	7.54724	59.36561
18	75	7.02941	60.30294
19	80	6.34559	61.16908
20	85	5.50078	61.83074
21	90	4.50026	62.63692
22	95	3.36819	63.26999
23	98.489	2.47901	64.21715
24	100	2.105925	67.20763
25	105	1.063872	78.19081
26	110	0.36585	92.45976
27	115	0.014339	108.7576

The results presented in Table 1 have a drawback. The calculated points with polar coordinates ρ_i and ψ_i are located on a non-uniform grid of angles ψ_i. This creates inconveniences when using the coordinates when creating programmes for numerically controlled machine tools. Furthermore, the number of coordinates is insufficient to ensure the required smoothness of the working surface of the cam. It is necessary to rearrange it on a uniform grid (ρ_i, ψ_i).

Modern computer numerical control (CNC) systems are designed to maximise automation by minimising human intervention. This ensures stable and uninterrupted operation, which supports smart manufacturing while delivering superior production outcomes.

CNC machine programming fundamentally relies on using standardised programming codes to communicate machining instructions. These codes define cutting tool trajectories and operational parameters for CNC operations.

Precision is crucial in machining, but it often proves challenging to replicate the exact dimensions of a CAD model. This is why machinists typically apply standardised tolerances that vary based on industry-specific requirements.

The obtained coordinate values of the profile points will be used to create the CNC machining program. However, to achieve the required part accuracy, a greater number of coordinates must be generated.

The essence of the rearrangement is that the straight sections of the accompanying broken line (ABL) connecting the calculated points ρ_i, ψ_i are replaced by convex curves, aiming for the minimum deviation from the calculated profile (Tables 2 and 3). The calculation scheme of rectilinear sections is presented in Fig. 1.

When tuning the engine camshaft, the law of tappet displacement is corrected. Based on these corrected values, calculations of other parameters are carried out using the methods presented in this paper and in [22].

Column 2 of Table 3 shows the coordinates of the existing profile on the grid $\Delta\varphi = 1°$, while column 3 indicates the coordinates of the tuning profile, and column 4 presents the deviations of the existing profile from the tuning profile.

Fig. 2 shows the contours of the cam calculated using the conventional method and the tuning cam.

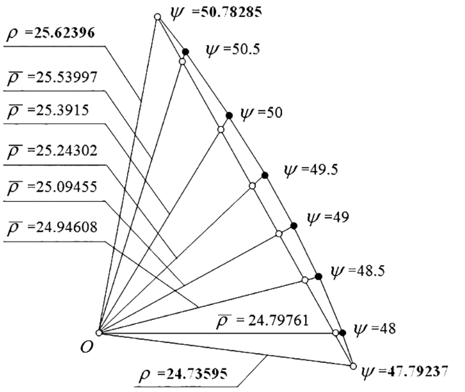

Fig. 1. Calculation scheme for increasing the density of points on a straight section of the ABL

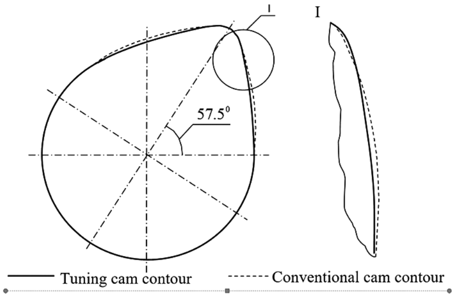

Fig. 2. Contours of the cam calculated using the conventional method and the tuning cam

Based on the research presented in the study, a camshaft was manufactured and installed in the vehicle's engine.

Tests of the Renault Duster 1.5 dCi equipped with the MT64WD engine and the tuned camshaft showed the results presented in comparative Table 4.

Conclusions. By analysing the existing publications, it was found that the emerging cyclic impact loads on the cam and tappet surfaces lead to premature wear of the cam profile and affect camshaft speed, valve movement, and torque. Tappet jump, occurring when the valve and seat surfaces make contact, causes a collision in the tappet-cam system. This leads to the destruction of the cam's working surface.

This paper introduces a universal methodology for designing the working profiles of cam mechanisms of ICEs, specifically, the method for obtaining the coordinates of the profile of the working surface of the cam of the camshaft of the ICE based on discrete differentiation of the tabular function.

In this study, a universal method for profiling the functional surfaces of tuned camshafts for heavy-, medium- and light-duty internal combustion engines is proposed, specifically, a method for obtaining the coordinates of the camshaft cam working surface profile based on discrete differentiation of a tabular function.

The calculations performed show that:

- the polar radius values $\overline{\rho}_i$ of the tuning cam completely correspond to the graph of displacement of S_i;

Table 2

Coordinates of cam profile points with a higher density

ψ, degrees	ρ, mm	ψ, degrees	ρ, mm	ψ, degrees	ρ, mm	ψ, degrees	ρ, mm	ψ, degrees	ρ, mm
0	18.7	12	19.2247	24	20.2008	36.5	22.0831	50.7829	25.6240
0.5	18.7089	12.5	19.2606	24.5	20.2761	36.8092	22.1296	51	25.6991
1	18.7178	13	19.2964	25	20.3514	40	22.8868	51.5	25.8723
1.5	18.7268	13.5	19.3323	25.5	20.4267	40.5	23.0055	51.7300	25.9519
2	18.7357	14	19.3682	26	20.5020	41	23.1241	52	26.0279
2.5	18.7446	14.5	19.4040	26.5	20.5772	41.5	23.2428	52.3631	26.1296
3	18.7536	15	19.4399	27	20.6526	42	23.3614	52.5	26.1637
3.5	18.7625	15.5	19.4758	27.5	20.7279	42.5	23.4801	53	26.2885
4	18.7714	16	19.5117	28	20.8032	43	23.5987	53.1693	26.3307
4.5	18.7804	16.5	19.5476	28.5	20.8784	43.5	23.7174	53.5	26.3997
5	18.7893	17	19.5835	29	20.9537	44	23.8360	53.8309	26.4687
5.5	18.7983	17.5	19.6193	29.5	21,0290	44.5	23.9547	54	26.4956
6	18.8072	18	19.6552	30	21.1043	45	24.7332	54.5	26.5752
6.2423	18.8115	18.5	19.6911	30.5	21.1796	45.5	24.1920	54.6971	26.6066
6.5	18.8300	19	19.7270	31	21.2549	46	24.3106	55	26.6429
7	18.8659	19.5	19.7628	31.5	21.3302	46.5	24.4293	55.5	26.6976
7.5	18.9019	20	19.7987	32	21.4055	47	24.5479	55.6344	26.7128
8	18.9377	20.5	19.8346	32.5	21.4808	47.5	24.6666	56	26.742
8.5	18.9735	21	19.8705	33	21.5561	47.7924	24.7360	56.3242	26.7679
9	19.0094	21.5	19.9064	33.5	21.6313	48	24.7976	56,5	26.7736
9.5	19.0453	22	19.9422	34	21.7066	48.5	24.9461	57	26.7897
10	19.0811	22.5	19.9781	34.5	21.7819	49	25.0946	57.1705	26.7952
10.5	19.1170	22.5402	19.9810	35	21.8572	49.5	25.2430	57.5	26.798
11	19.1529	23	20.0502	35.5	21.9325	50	25.3915	57.8297	26.7952
11.5	19.1888	23.5	20.1255	36	21.9631	50.5	25.5399	58	26.7897

Table 3

Coordinates of conventional and tuning profiles

ψ, degrees	ρ, mm	$\bar{\rho}$, mm	Δ	ψ, degrees	ρ, mm	$\bar{\rho}$, mm	Δ	ψ, degrees	ρ, mm	$\bar{\rho}$, mm	Δ
1	2	3	4	1	2	3	4	1	2	3	4
0	18.7	18.7	0	20	20.476	19.799	0.677	40	22.878	22.887	–0.009
1	18.771	18.718	0.053	21	20.571	19.871	0.7	41	23.105	23.124	–0.019
2	18.841	18.736	0.105	22	20.666	19.942	0.724	42	23.333	23.361	–0.028
3	18.911	18.754	0.157	23	20.761	20.050	0.711	43	23.561	23.599	–0.038
4	18.982	18.771	0.211	24	20.856	20.201	0.655	44	23.789	23.836	–0.047
5	19.052	18.789	0.263	25	20.951	20.351	0.6	45	24.017	24.073	–0.056
6	19.147	18.807	0.34	26	21.046	20.502	0.544	46	24.288	24.311	–0.023
7	19.242	18.866	0.376	27	21.141	20.653	0.488	47	24.584	24.548	0.036
8	19.337	18.938	0.399	28	21.236	20.803	0.433	48	24.881	24.798	0.083
9	19.432	19.009	0.423	29	21.331	20.954	0.377	49	25.176	25.095	0.081
10	19.527	19.081	0.446	30	21.426	21.104	0.322	50	25.471	25.392	0.079
11	19.622	19.153	0.469	31	21.521	21.255	0.266	51	25.752	25.699	0.053
12	19.717	19.225	0.492	32	21.616	21.405	0.211	52	26.021	26.028	–0.007
13	19.812	19.296	0.516	33	21.711	21.556	0.155	53	26.281	26.289	–0.008
14	19.907	19.368	0.539	34	21.805	21.707	0.098	54	26.489	26.496	–0.007
15	20.001	19.440	0.561	35	21.901	21.857	0.044	55	26.641	26.643	–0.002
16	20.096	19.512	0.584	36	21.995	21.963	0.032	56	26.741	26.742	–0.001
17	20.191	19.583	0.608	37	22.194	22.175	0.019	57	26.791	26.790	0.001
18	20.286	19.655	0.631	38	22.422	22.412	0.01	57.5	26.798	26.798	0
19	20.381	19.727	0.654	39	22.651	22.650	0.001	58	26.791	26.90	0.001

Table 4

Comparative indicators of the dynamic characteristics of a vehicle's diesel engine

Parameters	Value		Deviation, %
	Conventional camshaft	Tuning camshaft	
Maximum power, kW (hp)	85(115)	97(132)	+15
Maximum torque, Nm	260	330	+27
Number of revolutions, n/s	6,500	7,700	+18
Acceleration time up to 100 km/h, s	11.2	10.4	–7

- the tuning cam profile has a larger radius of curvature at the contact point between the cam and the tappet compared to the conventional one. This provides more favourable conditions for the formation of an oil wedge between the contact surfaces due to an increase in the hydrodynamic effective velocity at the interface;
- the method makes it possible to obtain a smooth surface that satisfies the specified tappet displacement diagram, allowing the desired valve timing characteristics to be achieved (Fig. 2);
- the application of software allows for the efficient control of the cam contour during manufacturing;
- the application of the methodology allows enhancing the efficiency of engines by improving the dynamic and speed characteristics of the flows.

The use of tuning camshafts, whose cam profile has been developed using the methodology proposed in this study, allows the engine to operate under load without noticeable interruptions, even when the crankshaft speed is reduced to its minimum limit. At the same time, the detonation threshold is shifted, eliminating piston knock ("pinging") at low and mid-range crankshaft speeds.

This effect is due to the fact that the higher and wider profile of the cams causes the valve to lift to a greater height (up to 10 mm) and remain open longer, ensuring a more complete intake of the air-fuel mixture. The smooth contour of such cams contributes to more reliable operation of the valve timing mechanism across wider timing phases.

In tuning engines, a noticeable reduction in fuel consumption (by 12 %) and a decrease in exhaust gas toxicity (by 15 %) have been observed. As a result, the engine becomes less prone to detonation, and its operational lifespan increases.

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Проєктування кулачків дизельних двигунів легкових автомобілів із покращеними динамічними характеристиками

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Мета. Автоматизація проєктування робочих профілів кулачкових механізмів двигунів внутрішнього згоряння як важкого, так і середнього й легкого типів із покращеними динамічними характеристиками.

Методика. Застосування дискретного диференціювання таблично заданого закону переміщення штовхача дозволило отримати неосцилюючі графіки швидкості та прискорення. На їх основі були визначені полярні координати профілю кулачка. CAD система SolidWorks використовувалася для створення тривимірної комп'ютерної моделі розподільного валу з поліпшеними динамічними характеристиками

Результати. Тюнінгові розподільні вали забезпечують оптимальну подачу повноцінного заряду суміші до циліндру шляхом збільшення висоти й швидкості підйому клапанів. Особливістю таких розподільних валів є те, що їх застосування відсуває межу детонації на малих частотах обертання колінвалу. Їхні кулачки відрізняються винятковою плавністю профілю, що забезпечує надійну роботу механізму газорозподілу. Зроблені розрахунки показують, що тюнінговий профіль кулачка має більший, порівняно із традиційним, радіус кривизни в точці контакту кулачка зі штовхачем, що забезпечує більш сприятливі умови утворення масляного клину між поверхнями контакту через збільшення гідродинамічно ефективної швидкості в поєднанні.

Наукова новизна. Упровадження нового підходу до проєктування розподільчих валів дозволило створити тюнінгові розподільчі вали, що забезпечують оптимальне наповнення циліндрів за рахунок максимізації висоти й швидкості підйому клапанів. Ключовою оригінальною особливістю є їх здатність підвищувати межу детонації на низьких обертах, що доповнюється виключно гладким профілем, який сприяє надійному регулюванню фаз газорозподілу.

Практична значимість. Розроблено універсальний метод профілювання функціональних поверхонь тюнінгових розподільних валів двигунів важкого, середнього й легкого типів, що забезпечує надійність і довговічність їх роботи.

Ключові слова: *двигун внутрішнього згоряння, тюнінговий розподільний вал, кулачок, газорозподільний механізм*

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