DOI: https://doi.org/10.15276/aait.08.2025.22
UDC 004.9

Method for automated control of rotor engine blade synchronization

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ABSTRACT

This study addresses the critical issue of synchronization accuracy in rotary-blade internal combustion engines, which directly influences their efficiency and operational reliability. Traditional mechanical synchronization methods suffer from significant drawbacks, including rapid wear, high maintenance costs, and limited modernization potential. To overcome these limitations, we propose an innovative electrical synchronization approach based on adaptive torque control of electric machines. The developed algorithm dynamically adjusts torque in real time according to the displacement of the bisector of the angle between the blades forming the combustion chamber, ensuring precise synchronization during each engine cycle.

A mathematical model was formulated to describe the relationship between torque, bisector displacement, and engine dynamics. This model was implemented in a custom simulation environment developed in JavaScript with interactive visualization tools. Computer simulations were conducted under various operating conditions to evaluate the algorithm's performance. Results demonstrate a substantial reduction in bisector displacement - from several degrees to thousandths of a degree and stabilization of cycle duration after only a few iterations. These findings confirm the algorithm's ability to maintain synchronization accuracy and improve engine stability. The proposed approach offers practical benefits for the design of advanced rotary-blade internal combustion engines, reducing mechanical wear and enhancing energy efficiency. Future research will focus on optimizing the correction factor, adapting the algorithm for engines operating under variable loads and temperatures, and integrating PID-based control strategies for improved responsiveness.

Keywords: automated control; computer modeling rotary-blade internal combustion engine, computer simulation, electrical synchronisation, torque control

For citation: **Ushenko Y. O., Uhryn D. I., Karachevtsev A. O., Halin Y. O., Ilin V. A. "Method for automated control of rotor engine blade synchronization".** ***Applied Aspects of Information Technology.*** **2025; Vol.8 No.3: 334–347. DOI: https://doi.org/10.15276/aait.08.2025.22**

INTRODUCTION

The efficiency and reliability of rotary-blade internal combustion engines (RBIEs) significantly depend on the accuracy of synchronization of their mechanical components. Traditionally, rotary engines use mechanical joints to synchronize shafts [1], [2], however, this method often leads to rapid wear of parts and a drop in engine efficiency due to alternating mechanical loads [3], [4], [5], [6], [7].

In recent decades, considerable attention has been paid to the development of alternative control methods, in particular through the use of reversible electric machines (they can operate as both a motor and a generator), which avoid some of the disadvantages of mechanical synchronization. According to US patent 10,472,965 B2, it is possible to effectively synchronize shafts using reversible electric machines controlled by electronic switches based on information from shaft position sensors [8].

This approach involves the use of feedback and control algorithms for precise torque control, but, as it turned out, there is insufficient regulation of a specific methodology that would lead to stable synchronization depending on the operational conditions and characteristics of the motor. In this context, the current study aims to develop an approach to controlling the torque of one of the MLRS shafts, which takes into account the displacement of the bisector of the angle between the blades that form the combustion chamber. Uniform rotation of the bisector of the angle formed by the blades is critical, as it indicates that there is no total moment acting on both blades. This means that although each blade may experience angular accelerations at certain points in time, the total angular acceleration of both blades will be zero. Accordingly, the bisector rotates at the same angular velocity, ensuring stable and efficient operation of the engine. The new approach is based on the analysis of dynamic changes in the position of the blades to stabilize the speed above the bisector and stabilize the engine cycle time. To validate the theoretical calculations, a number of experiments were carried out using computer modeling, the results of which demonstrate that the proposed approach really allows for the implementation of electrical synchronization. These results reinforce the potential of the new control approach for practical engineering and industrial applications, opening up new perspectives for the development of rotary-blade internal combustion engines [9], [10]. In conclusion, it is important to emphasize that the development of innovative control methods and approaches for rotary engines is key to the further advancement of these technologies [11]. The integration of modern control systems based on accurate scientific data and advanced technology can have a significant impact on the entire rotary engine industry, contributing to more durable, efficient and environmentally friendly solutions [12], [13].

ANALYSIS OF LITERATURE DATA

Synchronization of rotary engine components is critical to ensure its stability and efficiency [14]. According to John B. Hege, the synchronous operation of a Wankel rotary-blade engine provides a high energy utilization factor [15]. However, even small disturbances in synchronization can cause uneven operation, power loss, and reduced engine life [16]. This highlights the need to develop accurate control systems to minimize such errors and ensure stable combustion of the fuel mixture.

Traditional methods of synchronizing rotary engine blades use mechanical connections [17], [18], which lead to rapid wear. At the same time, the correct synchronization setting is necessary to avoid pressure losses and wear of gears operating at high speeds [19]. Current approaches, according to US patent 10,472,965 B2 [20], propose the use of revolving electric machines for synchronization, but they do not provide clear control methods. According to current research [21], [22], [23], adaptive torque variation can significantly improve this process, but there is currently a problem of unstable synchronization under dynamic changes in engine operation, which requires further study.

The study of synchronization of multi-motor systems, as shown in [24], demonstrates that even in hydraulic drives with a high level of automation, the key challenge is to reduce synchronization errors due to inertial effects. This emphasizes the importance of developing adaptive control systems to stabilize the operation of mechanisms with variable loads, which is also relevant for rotary internal combustion engines.

Most sources point to the problems of wear and tear and unreliability of mechanical methods, as well as the lack of optimized techniques for electrical synchronization systems. The first reason for this is the difficulty of integrating new technologies into existing designs, and the second is limited data on the real-time dynamics of the operation of the rocket launcher, which makes it difficult to accurately control torque [25], [26].

Computer simulation of a rotary engine is a key tool for predicting the behavior of the system under real loads: for example, W. Dong's study used modelling based on the Otto cycle to assess the impact of a new valve design on engine efficiency [27], and [28] created a software model of an internal combustion engine to analyze its parameters. Thus, the use of gas laws and computer simulations can help determine the optimal parameters for synchronizing the operation of rotary engine blades [29].

The work of M. Sakita presents a comparison of the efficiency of a rotary-blade internal combustion engine and a traditional piston engine using computer modeling. However, different modes of synchronization of the components of one RLV engine were not considered, which leaves this issue open for further research [30].

The review shows that there is a general unsolved problem of stabilizing blade synchronization using adaptive electrical systems under dynamic operating conditions. The research also demonstrates that computer modeling is an important tool for evaluating the effectiveness of different control approaches, allowing to optimize system parameters and predict its behavior under variable loads. The development of a new control approach that would allow controlling the torque adaptation depending on changes in engine operation could solve this problem. This is in line with the research objective set out in the next section and forms the basis for developing effective methods for practical implementation.

PROBLEM STATEMENT

The efficiency of rotary engines depends on the accuracy of blade synchronization. Mechanical synchronization methods have disadvantages, including wear and tear and maintenance costs. The lack of adaptive control models hinders the development of such engines, which needs to be addressed to improve their efficiency.

AIM AND OBJECTIVES OF THE STUDY

The purpose of the study is to develop and substantiate an adaptive algorithm for electrical torque control that ensures precise synchronization of rotary engine blades by accounting for dynamic changes during engine operation.

The goal of practical value is to demonstrate the provision of efficient and reliable synchronization of rotary engine blades using this approach. This includes the implementation of a system that allows for accurate response to dynamic changes in engine operation and optimization of engine performance using computer modelling.

To achieve this goal, the following tasks were set:

1) review existing approaches to torque control in rotary engines to justify the need for electrical synchronization in place of traditional mechanical coupling;

2) develop a mathematical and computational model of the adaptive torque-control algorithm, specifying its key parameters most notably the dependence on the displacement of the bisector between the blades and the correction gain K and the corresponding control law;

3) conduct experimental verification in a computer simulation environment to evaluate the effectiveness of the torque-control algorithm in stabilizing synchronization (reduction of bisector displacement and stabilization of cycle duration);

4) substantiate the practical applicability of the proposed approach based on the obtained results and outline directions for further development (tuning of K, PID augmentation, adaptation to variable loads and temperatures).

MATERIALS AND RESEARCH METHODS

The central part of this study is the development of a mathematical and computer model of torque control for electrically synchronized airborne missile launchers operating with motor generators mounted on engine shafts. The main purpose of the model is to dynamically adjust the torque transmitted to the electric machine to ensure optimal synchronization of blade rotation. A prerequisite for engine operation is the stability of the bisector rotation speed throughout its operation, so it was proposed to select the displacement of the bisector of the angle between the blades from the ideal position as the key control parameter.

Development of a mathematical model

The model is based on the analytical calculation of the processes of compression and expansion of gases in the engine chambers formed by the blades, on the analytical calculation of the kinetic energies of the shafts, as well as on sensor data reflecting the actual value of the angular coordinates of the blades.

The driving torque M transmitted to the shaft changes dynamically depending on the bisector displacement and is defined as:

$$M = \frac{A_g + dE \cdot X}{u_2 - u_1}, \qquad (1)$$

where A_g is the theoretically determined value of the gas work in the compression-expansion cycle, dE is the difference between the experimentally calculated total kinetic energy of the shafts and its theoretical value, u_1 and u_2 are the angular positions of the shafts taken from the sensors.

X is the correction factor, which is numerically determined as follows:

$$X = -O_b \cdot K, \qquad (2)$$

where O_b is the actual angular displacement of the bisector position from the ideal position, and K is a constant correction factor that affects the ‘offset damping’ time and can be selected empirically for motors with different characteristics. The minus before O_b is used to ensure correct torque correction against the bisector offset, thus maintaining control stability and symmetry. K is an important factor that changes the control speed.

Computer modelling and model parameters

The developed software for modelling the operation of a rotary-blade internal combustion engine is designed to analyze and optimize engine operation using mathematical modelling, physical laws and control algorithms. The model allows you to study in detail the dynamic processes occurring in the engine, including the intake of the working mixture, compression, combustion and exhaust of gases. The engine uses two shafts with blades that separate the volumes of gases in the chambers, ensuring that all four engine strokes run in parallel. The shaft coordinates are calculated as the angles of the blade position relative to the horizon, and the positive direction of rotation is defined as counterclockwise.

The model takes into account the polytrophic processes of gas compression and expansion, which allows taking into account the initial conditions of gas temperature and pressure, as well as further changes in parameters in each cycle. Combustion of

ISSN 2617-4316 (Print)
ISSN 2663-7723 (Online)

the mixture is initiated by a spark plug located at the zero coordinate.

The software allows you to enter key parameters such as the angular size of the blade, compression ratio, flash point, and the duration of the simulation breakdown section. The simulation calculates the chamber volumes, compression and expansion angles, pressures and temperatures of the gases.

The software package is implemented in JavaScript using jQuery and Chart.js libraries for visualization. The main functions include calculating engine dynamics, visualizing processes, and interactively controlling model parameters. Fig. 1 shows a screenshot of the software. The left side contains a parameter input panel where you can set key motor characteristics and simulation parameters. The right side displays graphs of shaft deflection and cycle times. The lower part shows an animated engine model that allows you to visually assess the position of the blades in different phases of operation, as well as a table with the results of calculations for each stroke, containing key parameters such as stroke number, stroke duration, shaft position and kbt bisector, combustion chamber temperature and pressure, gas operation, and electrical operation.

The model is a tool for analyzing dynamic processes in rotary-blade engines, adjusting parameters to optimize performance and for educational purposes. The software's flexibility allows users to experiment with different parameters and evaluate their impact on system performance.

The model supports interactive control, including real-time changes in ignition temperature.

Computer simulations of ideal engine operating parameters still show blade misalignment, as there is a problem of data rounding, and the simulation does not use an infinitesimal partition of the simulation time, but a finite one, and even under ideal conditions the bisector shifts. All model parameters,

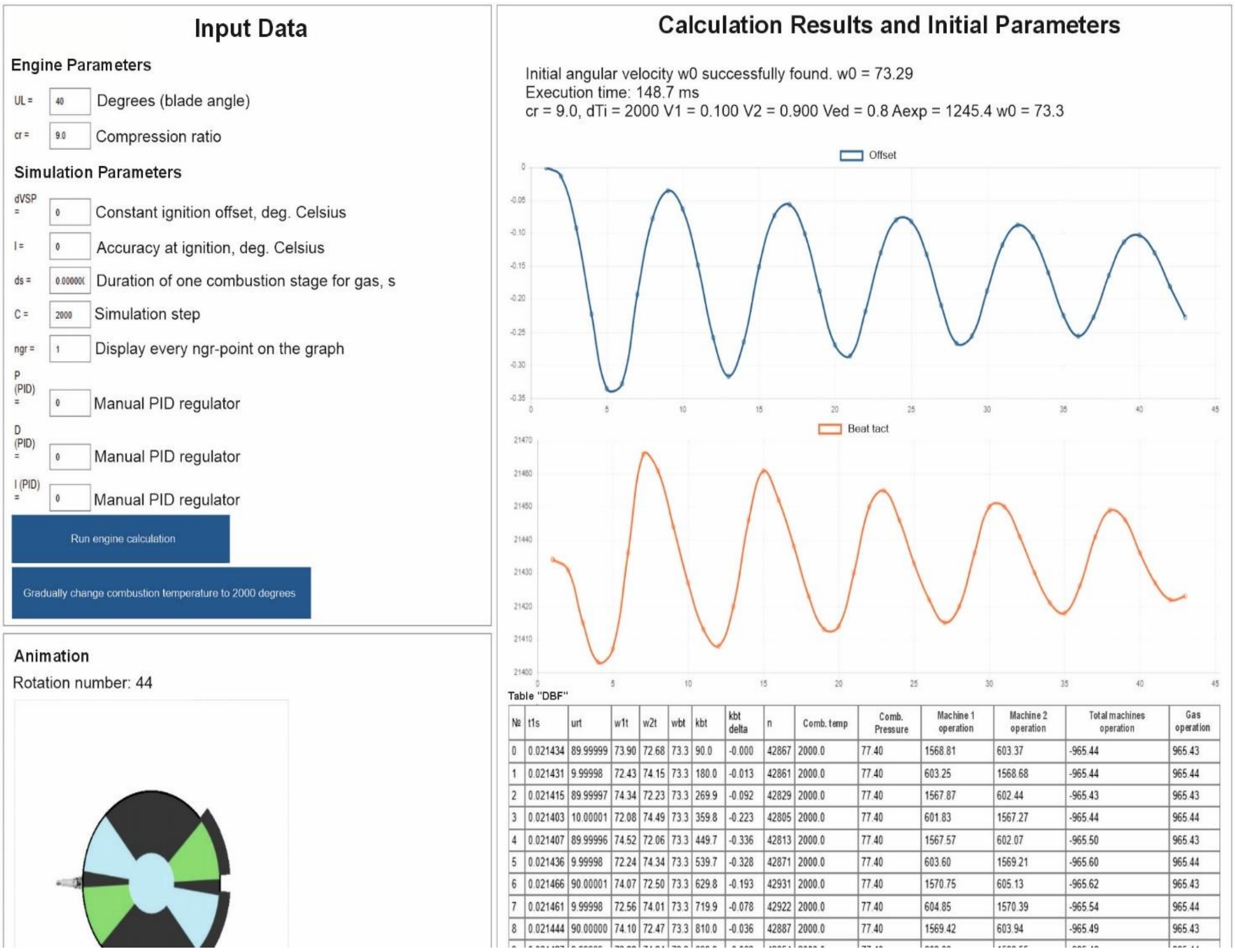

*Fig. 1.***Screenshot of the engine simulation software**
Source: compiled by the authors

including torque, bisector displacement, engine stroke duration, blade kinetic energy, and thermodynamic variables, are calculated by the computer model every $5 \cdot 10^{-7}$ seconds. The model allows simulating engine operation and monitoring the system's response to changing parameters in real time.

The parameters of the model for which the control experiments were conducted are listed below:

- angular size of the blades: 40°;
- shaft radius: 4.2 cm;
- motor radius: 12.5 cm;
- engine capacity: 3.2l;
- number of electric machines: 2 (on each of the shafts);
- compression ratio: 9.0 (this parameter indicates how many times the volume of the combustion chamber decreases from the largest to the smallest value);
- temperature at combustion of the stoichiometric mixture: 2000K (this parameter indicates the temperature increase inside the combustion chamber after ignition of the fuel mixture);
- constant correction factor: 1;
- workflow efficiency factor: 0.8 (an indicator that reflects the efficiency of converting the thermal energy of fuel into mechanical work);
- initial angular velocity of the shafts: 73.3 rad/s.

These parameters were used to set up and calibrate a mathematical model (selection of the optimal correction constant), which allows us to study the dynamics of torque changes depending on the shaft bisector displacement. The main goal was to ensure the stability of the bisector speed during all phases of engine operation, thereby optimizing its performance and increasing overall efficiency.

The described approach confirms theoretical calculations and provides a toolkit for precise and efficient control of the rotary engine operation.

RESEARCH RESULTS

The data obtained in the course of computer modeling of the rotary engine operation using the developed approach to torque control, as well as without it (with stationary theoretically calculated torque values) for comparison demonstrate the efficiency of the proposed approach.

Results of the computer model without control

To assess the basic characteristics of the engine without control, a series of experiments were conducted using a computer model. The goal was to determine the degree of bisector shift and changes in cycle duration in the absence of a control algorithm, which allows us to establish a starting point for further comparisons. The results clearly demonstrate that even under ideal initial conditions, the model shows a gradual accumulation of errors.

In particular, in the models of a single-engine motor (Table 1) and a two-engine motor (Table 2) without control, a significant bisector shift was recorded from the very first strokes. This indicates the instability of the system operation, which is accompanied by a gradual reduction in the duration of the strokes and a shift in the bisector. These results emphasize the need to implement a control system to stabilize the engine. To visualize the results of the experiment, Fig. 2 were constructed, which demonstrate graphically the dynamics of the bisector shift and changes in the cycle duration in a two-engine motor without a control algorithm. The figures clearly show how the bisector displacement increases with each subsequent cycle, accompanied by a gradual reduction in cycle duration. This trend indicates a systematic loss of synchronization, which confirms the conclusions drawn from the tables. This behavior of the motor without control is a direct consequence of the lack of mechanisms to compensate for the accumulation of errors.

Results of the computer model with control

After the implementation of the developed torque control algorithm, the movement of the bisector and the duration of the stroke were stabilized during all the strokes of the model. Table 3 shows the results of the experiment on the operation of the two-engine model using the control algorithm: the bisector and the stroke duration are maintained after simulating 340 strokes, and the torque value stabilizes after 10 strokes. Fig. 3 show that the bisector displacement is significantly reduced, which indicates high control accuracy, and the stroke duration remains stable after adjustment throughout the observation period, which confirms the reliability of the engine operation under the control of the developed algorithm. Fig. 3, Fig.4, Fig. 5 and Fig. 6 show how a change in the K – constant correction factor affects the time required to stabilize the system. The presented data indicate the validity of the study and demonstrate that the implementation of the described control algorithm can significantly improve the stability of rotary-blade engines. This approach allows other researchers to use the data presented to formulate their own conclusions and develop new control methods. Fig. 5 and Fig. 6 demonstrate that increasing the value of K to 2 and 2.3, respectively, increases the time required to stabilize the system.

ISSN 2617-4316 (Print)
ISSN 2663-7723 (Online)

Table 1. **Results of the computer model of a single-engine motor without control**

The tact	Ideal bisector coordinates at the beginning of a measure, deg °	Actual bisector coordinate at the beginning of the measure, deg	Bisector shift, deg	Beat tact, мs
1	0	0	0	14.55
2	90	90	0	14.55
3	180	180	0	14.52
4	270	269.8	-0.2	14.52
5	360	359.4	-0.6	14.47
6	450	448.9	-1.1	14.47
7	540	538.4	-1.6	14.43
8	630	627.6	-2.4	14.43
9	720	716.8	-3.2	14.4
10	810	805.9	-4.1	14.4
11	900	894.8	-5.2	14.37
12	990	983.7	-6.3	14.37
13	1080	1072.5	-7.5	14.34
14	1170	1161.2	-8.8	14.34
15	1260	1249.8	-10.2	14.31
16	1350	1338.3	-11.7	14.31
17	1440	1426.7	-13.3	14.28
18	1530	1515.1	-14.9	14.28
19	1620	1603.4	-16.6	14.26
20	1710	1691.5	-18.5	14.26

***Source*: compiled by the authors**

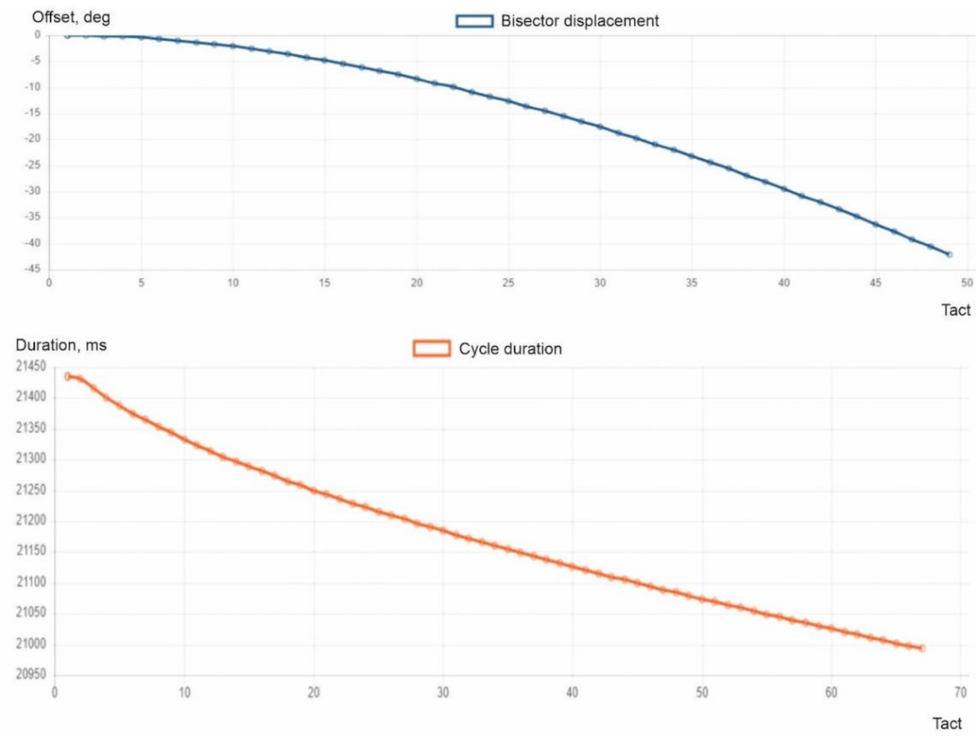

Fig. 2. **Dependencies of the bisector displacement on the ordinal number and cycle duration n its serial number of the stroke for a two-motor motor without control**

***Source:* compiled by the authors**

Table 2. **Results of the computer model of a twin-engine without control**

The tact	Ideal bisector coordinates at the beginning of a measure, deg	Actual bisector coordinate at the beginning of the measure, deg	Bisector shift, deg	Beat tact, мs
0	90	90	0	0.021434
1	180	180	-0.013	0.021431
2	270	269.9	-0.092	0.021415
3	360	359.8	-0.231	0.021401
4	450	449.6	-0.424	0.021388
5	540	539.3	-0.67	0.021375
6	630	629	-0.964	0.021364
7	720	718.7	-1.304	0.021353
8	810	808.3	-1.686	0.021343
9	900	897.9	-2.11	0.021333
10	990	987.4	-2.574	0.021323
11	1080	1076.9	-3.078	0.021314
12	1170	1166.4	-3.617	0.021305
13	1260	1255.8	-4.193	0.021297
14	1350	1345.2	-4.802	0.021289
15	1440	1434.6	-5.444	0.021281
16	1530	1523.9	-6.12	0.021273
17	1620	1613.2	-6.828	0.021265
18	1710	1702.4	-7.567	0.021258
19	1800	1791.7	-8.337	0.02125
20	1890	1880.9	-9.139	0.021243

***Source*: compiled by the authors**

DISCUSSION OF RESULTS

The simulation results confirm the significant impact of the developed control system on the stabilization of the rotary engine. The proposed approach has demonstrated effectiveness in both qualitative and quantitative terms.

Stabilization of the blade angle bisector can significantly reduce the risk of synchronization failures, which is critical for high-performance engines where accuracy and reliability are crucial.

From a qualitative perspective, the approach has demonstrated the ability to maintain the stability of motor performance parameters over time, as evidenced by the absence of significant fluctuations in the bisector angular displacement after the implementation of the control algorithm. This ensures uniform rotation of the shafts and prevents the accumulation of errors that lead to imbalances in the system.

In quantitative terms, the proposed system has significantly reduced the bisector displacement, reducing it from tens of degrees in the uncontrolled model to several thousandths of a degree in the controlled model. In addition, the stroke duration has stabilized, maintaining a constant value throughout all phases of engine operation.

These achievements are based on theoretical justifications and numerical experiments that confirmed the validity of the proposed approach. The data obtained can serve as a basis for further improvement of rotary engine control systems, in particular, for optimizing the constant correction factor K, adapting the algorithm for different types of engines, and modelling operating conditions with varying temperatures and loads.

Analyzing results without management

Without the use of a control algorithm, the simulations showed that the variability of the clock durations and bisector shifts can lead to serious malfunctions in the engine. This is especially evident in computer simulations of the motor: problems with data rounding and the fixed duration of the time step in the simulation cause the model of an ideal motor to be out of sync.

Table 3. **The results of the computer model of a twin-engine engine with control**

The tact	Ideal bisector coordinates at the beginning of a measure, deg	Actual bisector coordinate at the beginning of the measure, deg	Bisector shift, deg	Beat tact, мs
0	90	90	0	0.021434
1	180	180	0.044	0.021444
2	270	270.1	0.076	0.021441
3	360	360.1	0.084	0.021436
4	450	450.1	0.071	0.021431
5	540	540	0.048	0.021428
6	630	630	0.021	0.021427
7	720	720	-0.002	0.021428
340	30690	30690	0.008	0.021434
341	30780	30780	0.006	0.021433
342	30870	30870	0.006	0.021434
343	30960	30960	0.006	0.021434
344	31050	31050	0.006	0.021434
345	31140	31140	0.006	0.021434
346	31230	31230	0.006	0.021434
347	31320	31320	0.006	0.021434
348	31410	31410	0.006	0.021434
349	31500	31500	0.006	0.021434
350	31590	31590	0.006	0.021434

Source: **compiled by the authors**

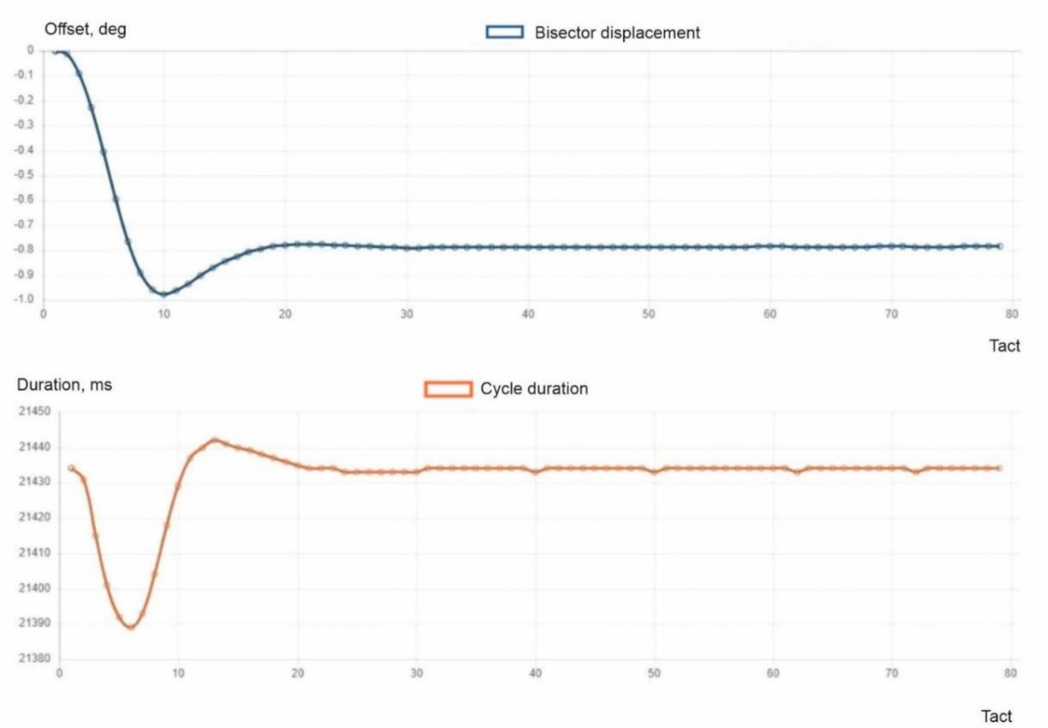

Fig. 3. **Dependencies of the bisector displacement on its ordinal number and cycle duration on its serial number for a two-engine motor with control for K=0.5**
***Source*: compiled by the authors**

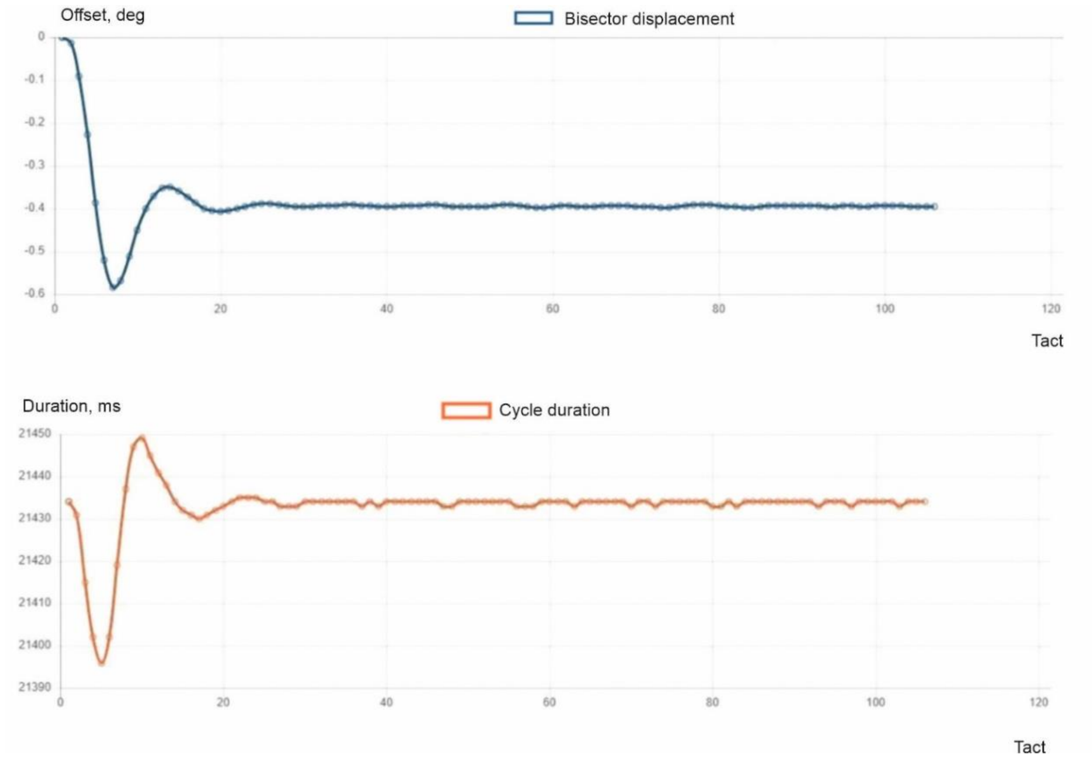

Fig. 4. **Dependencies of the bisector displacement on its ordinal number and cycle duration on its serial number for a two-engine motor with control for K=1**
***Source*: compiled by the authors**

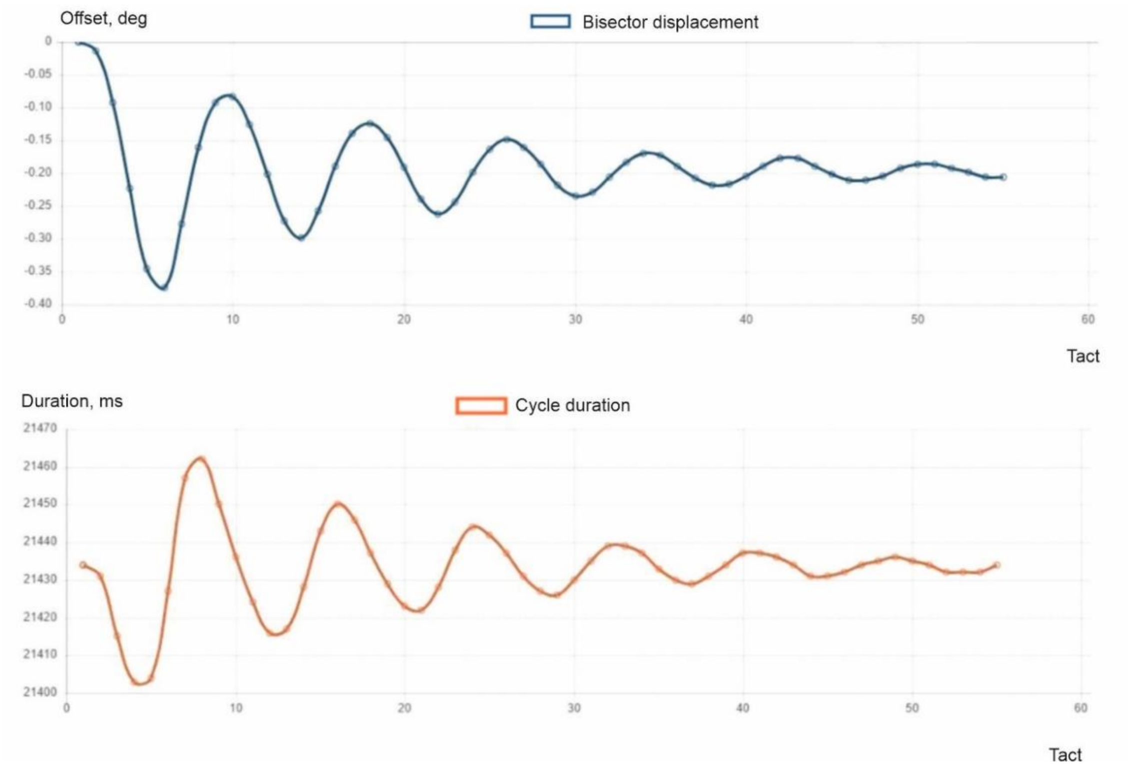

Fig. 5. **Dependencies of the bisector displacement on its ordinal number and cycle duration on its serial number for a two-engine motor with control for K=2**
***Source:* compiled by the authors**

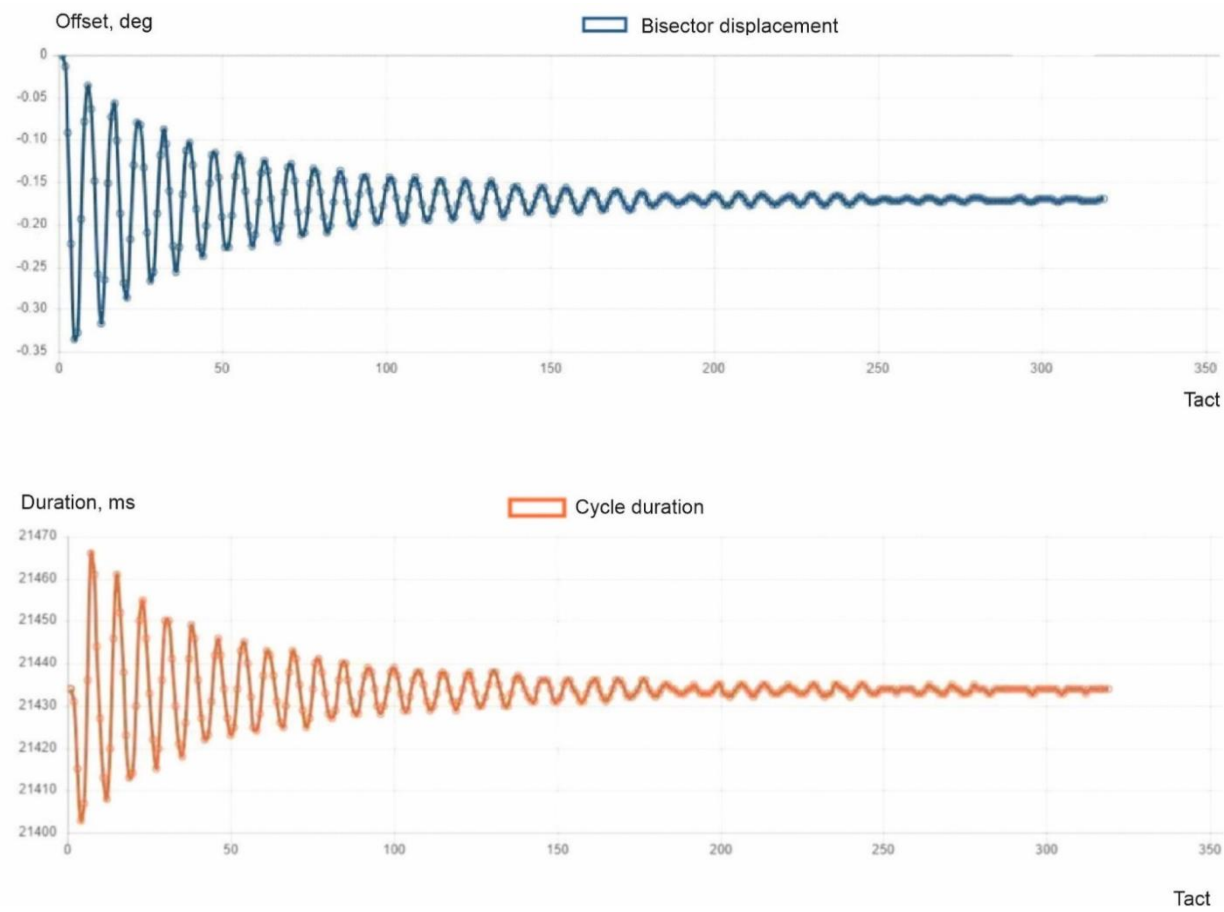

Fig. 6. **Dependence of the bisector displacement on its ordinal number and the cycle duration on its serial number for a two-engine motor with control for K=2.3**
***Source:* compiled by the authors**

Analyzing the results with control

The application of the developed algorithm quickly stabilized the engine operation, which confirms its effectiveness. The control system demonstrates high accuracy in correcting the bisector displacement and in correcting the engine cycle duration, which significantly improves the synchronization of its operation.

Technical challenges and areas for further research

One of the key aspects of torque control is the need to quickly change high currents, which is a technically challenging task. The challenge is to develop systems that can quickly respond to dynamic changes in motor operation. In future research, it will be valuable to develop PID control, as well as a control system that does not change the amount of torque, but changes the time during which this torque is applied to the shaft, which will allow for more efficient control of motor parameters.

Limitations of the existing model

Although the developed model demonstrates high efficiency, it still has limitations related to the analytically calculated blade starting speeds; this study did not investigate the engine starting from zero speed. Changes in temperature and load during engine operation can also affect the results, which require further analyses under different conditions. Comparison with other work and novelty This study proposes a new approach to torque control that takes into account dynamic changes in bisector displacement and uses torque correction to improve engine stability and efficiency. Compared to other works, this approach provides higher accuracy and reliability in engine synchronization, which makes it a significant contribution to the field of engine construction. The results of this work open up new opportunities for the development of more efficient and reliable rotary engines, and provide a basis for further research in this area.

CONCLUSIONS

This research is a study of the effectiveness of the method of automated torque control in rotary engines. The study showed that the proposed torque control approach is highly effective in ensuring the stability and reliability of rotary engines. The proposed model for automated control of the synchronization of rotary engine blades allows for precise torque correction depending on the bisector displacement, which contributes to the efficient synchronization of the blades. The obtained experimental results of the proposed system pave the way for further development and optimization of rotary engines, in particular by improving control systems.

1. The adaptive torque-control algorithm reduces synchronization error from ≈ 9.139° (no control, 20th cycle) to ≈ 0.006° (with control, steady-state's at 340–350th cycles) – a ~99.93 % decrease (~× 1,520) – while stabilizing cycle duration at 0.021434 s with residual variability ≤ ± 10 µs after settling; torque settles within ~10 cycles.

2. Robustness depends on the correction gain K: higher K (2.0–2.3) slows settling and increases transient peaks; K ≈ 0.5–1.0 yields fastest damping and the smallest steady-stet's drift.

3. For real-world's deployment, use reversible motor-generators on each shaft, high-resolution shaft encoders (≤ 0.01°), and power electronics with control loop ≥ 1 kHz (preferably 5–10 kHz), implementing online bisector estimation and proportional torque correction.

4. Energy efficiency was not directly measured; hardware validation on a physical test bench is required to quantify power/efficiency benefits under load and temperature variation.

Further research could focus on adapting the control algorithm for different models of rotary engines, including single-engine ones, as well as those operating under variable loads and temperature variations. This will allow us to test the versatility and adaptability of the approach and expand its application in different operating conditions. Another important area is to study the impact of different values of the correction constant K and optimize its value to achieve the best results, as well as to study the control system for starting the engine from zero speed.

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Conflicts of Interest: The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other, which could influence the research and its results presented in this article

Received 14.07.2025
Received after revision 11.09.2025
Accepted 23.09.2025

DOI: https://doi.org/10.15276/aait.08.2025.22
УДК 004.9

Метод автоматизованого керування синхронізацією лопатей роторного двигуна

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АНОТАЦІЯ

Це дослідження присвячене критично важливому питанню точності синхронізації в двигунах внутрішнього згоряння з обертовими лопатями, яка безпосередньо впливає на їхню ефективність та експлуатаційну надійність. Традиційні механічні методи синхронізації мають значні недоліки, включаючи швидкий знос, високі витрати на технічне обслуговування та обмежений потенціал модернізації. Щоб подолати ці обмеження, ми пропонуємо інноваційний підхід до електричної синхронізації, заснований на адаптивному регулюванні крутного моменту електричних машин. Розроблений алгоритм динамічно регулює крутний момент у реальному часі відповідно до зміщення бісектриси кута між лопатями, що утворюють камеру згоряння, забезпечуючи точну синхронізацію під час кожного циклу роботи двигуна.

Була сформульована математична модель для опису взаємозв'язку між крутним моментом, зміщенням бісектриси та динамікою двигуна. Ця модель була реалізована в спеціальному симуляційному середовищі, розробленому на JavaScript з інтерактивними інструментами візуалізації. Комп'ютерні симуляції проводилися в різних умовах експлуатації для оцінки ефективності алгоритму. Результати демонструють істотне зменшення зміщення бісектриси — з декількох градусів до тисячних градусів — та стабілізацію тривалості циклу вже після декількох ітерацій. Ці результати підтверджують здатність алгоритму підтримувати точність синхронізації та покращувати стабільність двигуна. Запропонований підхід пропонує практичні переваги для проектування сучасних двигунів внутрішнього згоряння з обертовими лопатями, зменшуючи механічний знос та підвищуючи енергоефективність. Майбутні дослідження будуть зосереджені на оптимізації коефіцієнта корекції, адаптації алгоритму для двигунів, що працюють під змінними навантаженнями та температурами, та інтеграції стратегій управління на основі PID для покращення реакції.

Ключові слова: автоматизоване управління; комп'ютерне моделювання; роторно-лопатевий двигун внутрішнього згоряння; комп'ютерна симуляція, електрична синхронізація, управління крутним моментом.

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