PROCESSOS DE PARTIDA DO MOTOR DE AUTOMÓVEL USANDO UM DISPOSITIVO DE ARMAZENAMENTO DE ENERGIA CAPACITIVO**THE STARTING PROCESSES OF A CAR ENGINE USING CAPACITIVE ENERGY STORAGES****ПРОЦЕССЫ ПУСКА АВТОМОБИЛЬНОГО ДВИГАТЕЛЯ С ИСПОЛЬЗОВАНИЕМ ЕМКОСТНЫХ НАКОПИТЕЛЕЙ ЭНЕРГИИ**

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RESUMO

O artigo apresenta os dados de experimentos relacionados ao processo de partida do motor de automóvel usando um dispositivo de armazenamento de energia capacitivo. É mostrado que os dispositivos de armazenamento de energia capacitivo podem ser usados para iniciar com eficiência o motor de combustão interna. O objetivo do artigo foi estudar os sistemas de partida elétrica de combustão de veículos com o dispositivo de armazenamento de energia capacitivo como fonte de energia elétrica utilizando um aparelho matemático que permitiu analisar o processo de partida do motor de veículo com energia capacitiva. No processo de trabalho, foram obtidas dependências analíticas do tempo e do ângulo de rotação do eixo de manivela do motor de combustão interna (número de cursos de trabalho) dos principais parâmetros do sistema de partida do arrancador elétrico com um momento constante de resistência no eixo do motor de combustão interna. Foram realizados os cálculos matemáticos e modelagem de modos operacionais em produtos de software especializados. Os resultados do experimento mostraram que o processo de rolagem do motor de combustão interna usando o arrancador elétrico quando é alimentado por dispositivos de armazenamento de energia capacitivo é significativamente diferente do processo de rolagem quando alimentado por uma bateria. Em conexão com o amplo uso de baterias em veículos e a busca de soluções tecnológicas alternativas para elas, pode-se dizer que os resultados obtidos neste artigo são de valor prático no quadro da moderna tecnologia de equipamentos elétricos.

Palavras-chave: *carga-descarga, dados experimentais, bateria de armazenamento, solução tecnológica alternativa, equipamentos elétricos modernos.*

ABSTRACT

The article presents data on experiments related to the start-up process of an automobile engine using capacitive energy storage. It is shown that capacitive energy storage devices can be used for efficient start-up of an internal combustion engine. The aim of the article was to study the systems of electric start of vehicles combustion with capacitive energy storage as source of electric energy using a mathematical apparatus that allowed analyzing the process of starting a vehicle engine with capacitive energy. In the course of work, analytical dependences on the time and angle of rotation of the crankshaft of the internal combustion engine (number of working strokes) of the main parameters of the electric starter starting system with a constant moment of resistance on the shaft of the internal combustion engine were obtained. Mathematical calculations and simulation of operating modes in specialized software products were carried out. The results of the experiment showed that the process of scrolling the internal combustion engine with an electric starter when it is powered from capacitive energy storage devices differs significantly from the process of scrolling when powered from a rechargeable battery. Due to the large proliferation of batteries in vehicles and the search for alternative

technological solutions to them, it can be said that the results obtained in this article are of practical value in the framework of modern electrical equipment technology.

Keywords: charge-discharge, experimental data, rechargeable battery, alternative technological solution, modern electrical equipment.

АННОТАЦИЯ

В статье представлены данные об экспериментах, связанных с процессом запуска автомобильного двигателя с использованием емкостного накопителя энергии. Показано, что емкостные накопители энергии могут использоваться для эффективного запуска двигателя внутреннего сгорания. Целью статьи является изучение систем электрического запуска сгорания транспортных средств с емкостным накопителем энергии в качестве источника электрической энергии с использованием математического аппарата, который позволил проанализировать процесс запуска двигателя транспортного средства с емкостной энергией. В процессе работы были получены аналитические зависимости от времени и угла поворота коленчатого вала двигателя внутреннего сгорания (числа рабочих ходов) основных параметров системы запуска электростартера с постоянным моментом сопротивления на валу двигателя внутреннего сгорания. Проведены математические расчеты и моделирование режимов работы в специализированных программных продуктах. Результаты эксперимента показали, что процесс прокрутки двигателя внутреннего сгорания с помощью электростартера при его питании от емкостных накопителей энергии значительно отличается от процесса прокрутки при питании от аккумуляторной батареи. В связи с большим распространением аккумуляторов в транспортных средствах и поиском альтернативных технологических решений для них можно сказать, что результаты, полученные в этой статье, имеют практическую ценность в рамках современной технологии электрооборудования.

Ключевые слова: заряд-разряд, экспериментальные данные, аккумуляторная батарея, альтернативное технологическое решение, современное электрооборудование.

1. INTRODUCTION

Analysis of the state and development of modern systems of electric starter systems (ESS) shows that their output parameters are affected by electrical and mechanical losses, the design of the drive mechanism, and the operating mode of the starter. The existing constructive and technological measures to improve these factors have reached optimal values, and it is not possible to improve the output parameters of the ESS due to their change (Shi *et al.*, 2005; Hata *et al.*, 2015; Jung *et al.*, 2015; Munakata and Kanamura, 2015; Ogundiran *et al.*, 2017).

At present time lead acid rechargeable batteries (AB) are used overwhelmingly as sources of electrical energy in electric starter systems (ESS) of internal combustion engines (ICE) of vehicles. The main disadvantage of it is low utilization of stored energy at negative temperatures, due to the high internal resistance, which complicates the process of starting the internal combustion engine (Keshan *et al.*, 2016; Grachev *et al.*, 2017; Subramanian, 2017; Kroics, 2018; Kunt, 2018; Ramazanov *et al.*, 2018; Dhundhara and Verma, 2018; Sulym *et al.*, 2018; Ha, 2019). In this regard, capacitive energy storages (ECs) are very promising. They have significantly lower internal resistances compared

with AB and higher specific powers (Cheremisin *et al.*, 2015; Karmazin *et al.*, 2015; Vatamanu and Bedrov, 2015; Ishmatov *et al.*, 2016; Opila, 2017; Dong *et al.*, 2017; Fomin *et al.*, 2018; Hulea *et al.*, 2018; He *et al.*, 2019).

The use of ESS with energy storage devices (CES) makes it possible to maintain the nominal voltage of the vehicle and apply low-voltage CES both on promising and on serial automobile engines with almost no modification of the elements of the ESS (Waters *et al.*, 1979; Xie *et al.*, 2016; Crouch, 2017; Luo *et al.*, 2017; Malozyomov *et al.*, 2018; Xu *et al.*, 2018; Bae and Park, 2018; Tishkov *et al.*, 2019; Kuznetsov and Artemenko, 2019; Shao *et al.*, 2019).

The initial dates in the design of ESS are minimum starting speed n_{min} , average static moment of resistance ICE M_s , corresponding n_{min} and starting time t_s at the limit (minimum) temperature of the reliable starting t_{0min} . Therefore, for a theoretical analysis of the processes occurring in an ESS with an CES in the first approximation, it can be assumed that the shaft of an internal combustion engine is loaded with a constant static moment of resistance M_r . Neglecting also the moment of inertia of the system "electric starter – internal combustion engine", uneven rotation of the engine shaft and starter inductance, the following

main results were obtained (Kroics, 2015; Manla *et al.*, 2015; Hiramatsu *et al.*, 2015; Saito *et al.*, 2015; Geetha and Subramani, 2017; Xu *et al.*, 2017).

This article presents the results of a theoretical and experimental study of the ESS ICE with CES. The evaluation of the effectiveness of electric start-up systems using energy storage devices at low temperatures was carried out. The aim of the article was to study the systems of electric start of internal combustion of vehicles with capacitive energy stores as sources of electric energy using a mathematical apparatus, which allowed to analyze the process of starting a car engine using capacitive energy stores. The results obtained as a result of research will be used in the development and justification of the requirements for a start-up system with energy storage devices, which will increase the performance of automotive vehicles at low temperatures.

2. MATERIALS AND METHODS

The study was conducted in the framework of the methodology of the physical foundations of electrical engineering and electronics, including using the method of analogy and forecasting. According to the method proposed by the authors earlier (Maleev and Shmatkov, 2013a; Maleev and Shmatkov, 2013b; Korotkov *et al.*, 2015; Maleev *et al.*, 2015; Khortov *et al.*, 2016a; Khortov *et al.*, 2016b; Skvortsov *et al.*, 2016; Akimov *et al.*, 2017; Shmatkov and Lavrikov, 2017; Zuev *et al.*, 2017) and taking into account the assumptions presented above, a mathematical apparatus was used that allowed the authors to analyze the process of starting a car engine using capacitive energy storage devices.

So at a constant moment of resistance M_r , the current intensity of the electric starter (ST) armature will also be constant (Equation 1) (Korotkov *et al.*, 2015) where η_{tr} – transmission efficiency from ST to ICE ($\eta_{tr} = 0.85$) (Maleev *et al.*, 2015); η_{em} – electromagnetic efficiency ST ($\eta_{em} = 0.75-0.95$); i – is the gear ratio of the drive from the ST to the internal combustion engine; C_m – constant ST; ϕ is the main magnetic flux of ST excitation. If the CES is charged to the initial voltage U_{coi} and has an internal resistance R_c , then at a constant discharge current $i_c = I_a$ all the main parameters of the ESS will decrease linearly with time t (Figure 1).

The voltage at the terminals of the CES (Equation 2) (Maleev and Shmatkov, 2013a)

where c – is the capacity of CES. CES voltage under load (Equation 3) (Maleev and Shmatkov, 2013b) where Equation 4 is time constant CES (Akimov *et al.*, 2017). EMF at starter anchor (Equation 5) (Khortov *et al.*, 2016a) where ΔU_b – voltage drop under brushes ST (with $I_a = \text{const}$, $\Delta U_a = \text{const}$); R_w – wire resistance from CES to ST; R_{ST} – the total resistance of the ST, which includes the resistance of the excitation windings and armature (Equation 6) (Skvortsov *et al.*, 2016) is discharge time constant CES. ST armature speed (Equation 7) (Khortov *et al.*, 2016b) where c_c – constant ST. Electromagnetic power ST (Equation 8) (Shmatkov and Lavrikov, 2017). Time t_k during which ST rotates (until it stops) (Equation 9) (Zuev *et al.*, 2017). CES voltage at which ST stops (Equation 10) (Zuev *et al.*, 2017).

According to Equations 1-10, an analysis was made of the starting processes of an automobile engine using capacitive energy storage devices to obtain numerical results.

3. RESULTS AND DISCUSSION:

After stopping ST, it occurs discharge CES on the active resistance in the starter circuit, but this process is not of interest due to the lack of useful work. The dependence of the ESS parameters on the angle of rotation ϕ of the crankshaft of the ICE and on the number of engine power strokes N_{px} is much more complicated. The rotation angle ϕ of the engine crankshaft given by the following relationship (Equation 11): where Equation 12 is the angular frequency of rotation of the engine crankshaft, s^{-1} ; n – rotational speed of the engine crankshaft, min^{-1} .

The number of working strokes of the internal combustion engine is determined by the Equation 13. The angular frequency of rotation ω linearly depends on time t (Equation 14) where Equation 15 is maximum angular speed of the crankshaft at the start cranking; t_k – cranking time of the engine crankshaft. Substituting Equation 14 into Equation 11 and after transformations, Equation 16 is obtained. From Equation 14, after the conversion, you can get the expression for the current time (Equation 17). Substituting Equation 17 into Equation 16, after transformations, Equation 18 will be gotten where Equation 19 is the full angle of rotation of the engine crankshaft. Equation 20 is obtained from the Equation 18.

The change in ϕ/θ in the function n/n_{max}

is shown in the Table 1. The dependence of φ/θ on $n/n_{\max}$ is shown on the Figure 2. Table 1 shows the values of n and φ obtained in the course of calculations. The adduction of φ/θ and $n/n_{\max}$ allows us to simplify the calculation and increase the accuracy of the results obtained. The $n/n_{\max}$ step was set by the heuristic method in the range from 1.0 to 0.0 with a step of 0.1. The calculation of φ/θ in table 1 was carried out according to Equation 20. From the Equation 18 can be obtained the equation that determines the change in the frequency of rotation on the angle of rotation (Equation 21). The dependence of $n/n_{\max}$ in the function φ/θ is shown in Figure 2. As can be seen, with a frequency of n greater than Equation 22, the crankshaft rotates in the range of the angle of rotation φ from 0 to 75–0.

Figure 3 shows the dependence of φ/θ and $n/n_{\max}$ on a relative time t/t_k . The obtained results allow to draw the following important conclusions. If the average rotational speed n_{av} is equal to the minimum starting frequency of rotation $n_{\min}$, then within 3/4 of the full angle of rotation of the crankshaft θ , it will rotate at a frequency greater than $n_{\min}$. This significantly improves the process of mixing, facilitates the ignition of the combustible mixture, increases the efficiency of its combustion, i.e. facilitates the process of starting the engine. In this case, the required start time should be shorter than when powered by the ST from the battery when the engine crankshaft is turned at a frequency of $n_{\min}$.

The Figure 4 shows the dependence of the ESS-parameters on the angle of rotation and the number of working strokes of the ICE – NWS. Experimental studies were carried out in the laboratory of the department "Electrical equipment and industrial electronics" of the Moscow Polytechnic University. The object of the test was the four-cycle, four-cylinder, injection engine of a modern small-volume car with a working volume of 1.7 liters. CES consisted of several dozen individual high-voltage electrolytic capacitors (type K50-17 with a capacity of 200 mkF each (Kwright et al., 1990)) with a total capacity of 0.1277 F. The initial charge voltage for CES was $U_{\text{coi}} = 290$ V. As the ST was used own standard industrial DC electromotor (220 V) JB-061-M64 with a front cover, a traction relay and a drive mechanism from a starter 35.3708. The total gear ratio of ST-ICE is 11,7. Figures 5 and 6 show the variation in the instantaneous and average values of the engine crankshaft rotational speed (n and n_{av}), the torque of the starter, adduced to the crankshaft ($M_{\text{st}} = M_{\text{sti}} \times \eta_{\text{tr}}$ and $M_{\text{st.av}}$) and the voltage at the CES-terminals

U_c depending on from time t and crank angle φ (number of working strokes N_{ws}) at a temperature of -15C (oil viscosity 1150 mm²/s).

As can be seen, the process of scrolling of the internal combustion engine with an electric starter when it is powered from CES is significantly different from the process of scrolling when it powered from an AB (Figure 7). In the initial period of operation, ST develops a large torque (Equation 23), which is necessary to overcome the moment of resistance and dynamic moment. (Figures 5, 6). Then, as the crankshaft is turning, due to a decrease in the viscosity of the oil in the friction pairs of the internal combustion engine and the rotational speed decreases, the torque of the rotational resistance and the torque of the starter M_{st} decreases and most of the time the scrolling occurs with a constant torque.

The rotational frequency n initially increases rapidly during 0.33 s to a value of $n_{\max} = 520 \text{ min}^{-1}$, and then decreases linearly as it discharges and decreases sharply to zero at the end of the rotation. The average frequency of rotation of its scrolling time $t_n = 1.436$ s is 327 min^{-1} . The sharp increase in the rotational speed at the initial moment compared with the gradual increase in the frequency when powered from the battery (Figure 7) is due to the high voltage CES. The absence of stages with a constant scrolling frequency is caused by a change in the voltage CES U_c according to its discharge. The voltage at the terminals of the CES – U_c is significantly reduced at the beginning of the scrolling, when the moment of resistance, the torque M_{st} and the required current consumed from the CES to provide this torque are higher. The CES voltage U_c and the rotation frequency n decrease linearly most of the time (from 0.619 s to 1.262 s) while scrolling occurs with practically constant M_{st} (and, therefore, with a constant starter current $I_a = 14.9\text{-}14.3$ A), which corresponds to aforecited theoretical studies.

The sharp decrease in rotational speed at the end of the scrolling process is due to the fact that at a certain voltage CES, the generated power becomes insufficient to overcome the increasing moment of resistance due to compression of the fuel-air mixture in one engine cylinder. Changing of the net power P developed at ST, energy W_{co} and number of strokes N_{px} depending on the time is shown in Figure 8 in addition to the dependencies n , M_{st} and equation 24. At the same time, Figure 8 shows the calculated dependences of the CES-voltage U_{calc} and the crankshaft rotation speed n_{calc} . The

maximum of ST-power $P_{2\max} = 4471 \text{ W}$ will be developed at the stage of acceleration ($t = 0.055 \text{ s}$) at a sufficiently high moment of resistance and voltage of CES.

The CES-energy (Equation 25) during cranking of the engine crankshaft $t_s = 1.436 \text{ s}$ is decreasing due to the CES-discharge from 5370 J to 379 J. The engine performs 17 working strokes during the scrolling time t_s . If to think that the cranking of the engine crankshaft occurs with a constant average moment of resistance and an average current of the starter armature 14.6 A, then with the total resistance of the starter circuit (including resistance of the ES, the resistance of the excitation windings and starter armature, the resistance of the collector exact node and resistance of the wires), equal to 9.14 ohms, the estimated time of cranking of the engine crankshaft to the stop t_k is equal to 1.387 s versus 1.436 seconds in the experiment. The calculated values of voltages of CES U_{calc} quite closely coincide with the experimental values.

Significant discrepancies between the calculated (n_{calc}) and experimental rotational frequencies of the crankshaft of the ICE are primarily explained by the change in the main magnetic excitation flux of the ST in the scrolling process, which is not taken into account in the calculation. The test results showed that scrolling of the ICE from high-voltage ES comparing to scrolling from AB differs in significantly lower operating currents ($I_{u.\text{av.}} = 14\text{-}20 \text{ A}$ versus $I_{u.\text{av.}} = 200\text{-}300 \text{ A}$), more higher rotational frequencies of the engine crankshaft ($n_{\text{av}} = 327 \text{ min}^{-1}$ versus $n_{\text{av}} = 140 \text{ min}^{-1}$) and significantly less scrolling time ($t_s = 1.436 \text{ s}$ versus $t_s = 10 \text{ s}$). A decrease in the operating current ST and an increase in the crankshaft speed is explained primarily with an increase in the power supply voltage (CES). The CES as it is discharged. The reduction of operating current ST allows reducing the cross-section of wires from CES to ST, which reduces the mass-dimensional indicators of the ESS. At the same time, heat losses in the ESS are reduced, which increases its efficiency.

Increased engine cranking frequency facilitates the start process and, in accordance with the starting characteristics of the engine, the start time is reduced. Therefore, despite the fact that the scrolling time of the internal combustion engine with NE is reduced, the engine can be started due to an increase in the rotational speed of the engine crankshaft. At the same time, the test results showed that for a reliable start of the ICE of a modern small-sized car with a high-

voltage CES at a temperature of -15°C , the starting characteristics of the injection need to be changed.

4. CONCLUSIONS:

According to the results of the research, the following most important results can be briefly highlighted:

1. Analytical dependences on the time and angle of rotation of the engine crankshaft (the number of working strokes) of the basic parameters of the ESS, with a constant moment of resistance on the engine shaft. The experimental results show the possibilities of practical use of the proposed calculation methods after taking into account the influence of dynamic factors on the characteristics of the ESS in the CES.

2. The influence of dynamic factors on the characteristics of ESS with CES should be taken into account after statistical data processing of ICE with CES of starting tests in different climatic conditions. For reliable start-up of an internal combustion engine with high-voltage CES at a temperature of $(-15 \div -25)^\circ \text{C}$, a change in its starting characteristics is required. Moreover, experimental studies have shown that at temperatures $(-20 \div -25)^\circ \text{C}$ ESS starts were carried out using an electric starter with an additional gearbox.

3. The process of cranking the crankshaft ICE when the electric power from the high voltage CES differs from the power supply from a AB by significantly lower operating currents ST, higher frequencies and smaller scroll time. It is also worth noting that an increase in the value of the capacity of the CES and the value of the initial charging voltage of the CES allows increasing the scroll time, the number of working strokes of the internal combustion engine, the average and maximum rotational speeds of the crankshaft of the engine, and the useful power of the electric starter, however, a detailed analysis of these characteristics is beyond the scope this study.

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$$Ia = \frac{Mr}{\eta_{tr} \times \eta_{em} \times i \times Cm \times \phi} \quad (\text{Eq. 1})$$

$$U_{co} = U_{coi} - \frac{Ia}{c} \times t \quad (\text{Eq. 2})$$

$$Uc = U_{co} - Ia \times Rc = U_{coi} - \frac{Ia}{c} (t + \tau_c) \quad (\text{Eq. 3})$$

$$\tau_c = R_c \times C \quad (\text{Eq. 4})$$

$$Ea = U_{coi} - \Delta Ua - Ia (Rc + Rw + R_{ST}) \left(1 + \frac{t}{\tau}\right) \quad (\text{Eq. 5})$$

$$\tau = C \times (R_c + R_w + R_{ST}) \quad (\text{Eq. 6})$$

$$na = \frac{U_{coi} - \Delta Ub - Ia (Rc + Rw + R_{ST})}{Cc \times \phi} \left(1 + \frac{t}{\tau}\right) \quad (\text{Eq. 7})$$

$$p = \left[U_{coi} - \Delta Ub - Ia (Rc + Rw + R_{ST}) \times \left(1 + \frac{t}{\tau}\right) \right] \times Ia \quad (\text{Eq. 8})$$

$$t_K = ((U_{coi} - \Delta Ub) \times c) / Ia - \tau \quad (\text{Eq. 9})$$

$$U_{coK} = Ia \times (Rc + Rw + R_{ST}) + \Delta Ub \quad (\text{Eq. 10})$$

$$\Phi = \int \omega dt \quad (\text{Eq. 11})$$

$$\omega = \frac{\pi \times n}{30} \quad (\text{Eq. 12})$$

$$N_{WS} = \frac{\Phi}{\pi} \quad (\text{Eq. 13})$$

$$\omega = \omega_{max} - \frac{\omega_{max}}{t_K} \times t \quad (\text{Eq. 14})$$

$$\omega_{max} = \frac{\pi \times n_{max}}{30} \quad (\text{Eq. 15})$$

$$\Phi = \int \omega dt = \int (\omega_{max} - \omega_{max}/t_K \times t) dt = \omega_{max} \times t \times (1 - t/(2 \times t_K)) \quad (\text{Eq. 16})$$

$$t = \frac{\omega_{max} - \omega}{\omega_{max}} \times t_K = \left(1 - \frac{\omega}{\omega_{max}}\right) \times t_K \quad (\text{Eq. 17})$$

$$\begin{aligned} \Phi &= \omega_{max} \times \left(1 - \frac{\omega}{\omega_{max}}\right) \times t_K \times \left[1 - \frac{\left(1 - \frac{\omega}{\omega_{max}}\right) \times t_K}{2 \times t_K}\right] = \\ &= \frac{t_K \times \omega_{max}}{2} \times \left[1 - \left(\frac{\omega}{\omega_{max}}\right)^2\right] = \Theta \times \left[1 - \left(\frac{\omega}{\omega_{max}}\right)^2\right], \end{aligned} \quad (\text{Eq. 18})$$

$$\vartheta = \frac{t_K \times \omega_{max}}{2} \quad (\text{Eq. 19})$$

$$\frac{\Phi}{\Theta} = 1 - \left(\frac{\omega}{\omega_{max}}\right)^2 = 1 - \left(\frac{n}{n_{max}}\right)^2 \quad (\text{Eq. 20})$$

$$n = n_{max} \times \sqrt{1 - \frac{\Phi}{\Theta}} \quad (\text{Eq. 21})$$

$$n_{av} = \frac{n_{max}}{2} \quad (\text{Eq. 22})$$

$$M_{st} = 280N \times m \quad (\text{Eq. 23})$$

$$U_c = f(t) \quad (\text{Eq. 24})$$

$$W_{co} = \frac{C \times U_c^2}{2} \quad (\text{Eq. 25})$$

Figure 1. The dependence of the ESS parameters on time at a constant discharge current

Figure 2. The dependence of the engine speed on the angle of rotation in relative units

Figure 3. The dependence of the rotational speed of the crankshaft ICE on the angle of rotation, to the rotation time, in relative units

Figure 4. Estimated change of ESS-parameters on the angle of rotation and the number of working strokes of the engine

Figure 5. The dependence of instantaneous and average ESS-parameters to the time cranking of the engine

Figure 6. The dependence of instantaneous and average ESS-parameters on the angle of rotation and the number of working strokes of the engine

Figure 7. The dependence of the frequency and moments of the starter resistance when it powered by a battery

Figure 8. Experimental dependencies of the ESS-parameters depending on the engine scrolling time

Table 1. Values of n and φ obtained in the course of calculations

$n/n_{\max}$	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0
φ/ϑ	0.19	0.36	0.51	0.64	0.75	0.84	0.91	0.96	0.99	1.00