UDC 629.735.015.3 (045)

[1]M. F. Tupitsin,
[2]A. A. Ziganshin,
[3]I. O. Stepanenko

EXPERIMENTAL CHECKING OF REVERSIBILITY THEOREM FOR AXIALLY SYMMETRIC BODY WITH EMPENNAGE

Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine
E-mails: [1]nift@mail.ru, [2]anwarzihan@gmail.com, [3]STEPANENKO.iLay@gmail.com

Abstract**—***Wind tunnel tests were implemented for experimental verification of the reversibility theorem for three various shapes of fore body for an axially symmetric thin body in direct and reverse streams. Besides, such tests were implemented for UAV models with three types of wings. Results of investigations showed that the error of execution reversibility theorem consequence can achieve 12.5% at the range of angles of attack from 0 to 20° (accordingly, from 180° to 200°).*

Index Terms—Reversibility theorem, airfoils, direct and reverse streams, aerodynamic characteristics; analysis (mathematics); subsonic flow; drag and lift force coefficients.

I. INTRODUCTION

In series of impotent tasks connected with calculations of motion of airfoils in the air, it is necessary to have their aerodynamic characteristics at an angles of attack from 0 to 180° or 360° [2], [5]. In particular, these aerodynamic characteristics should be used for UAV which is launched from an aircraft against direction of its movement [4]–[6].

Usually, a take-off (start) of UAV from the aircraft is performed in the direction of its movement, but there is a method of UAV takeoff from the aircraft in the reverse direction of its movement [5].

The advantage of this tactical method is following: a significant portion of the space in the rear hemisphere of the aircraft will be reached faster by UAV (Fig. 1).

Let assume an aircraft *1* moves along the trajectory *5* and a need arises to deliver specified cargo to point *B*. At takeoff of UAV *3* from aircraft *1* in the direction of its movement, it should make a turn with the highest possible overload and move along the trajectory *2*. At takeoff of UAV *3* against the direction of movement aircraft *1*, the distance covered (trajectory *4*) is significantly shorter and time of flight is less.

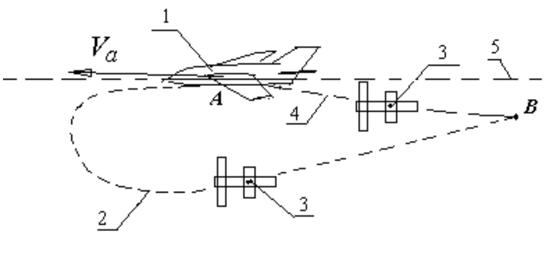


Fig. 1. Flight trajectories of UAV at takeoff from aircraft along and against direction of its movement

Receiving of reliable aerodynamic characteristics is a consuming and expensive process, and an application of the reversibility theorem (RT) allows reducing the price of development and modernizing perspective UAVs.

It is known [1], [3] that the RT in aerodynamics sets the integral relationship between the downwashes and aerodynamic loads on a thin wing with a direct (V_f) and reverse (V_r) streams:

$$\Delta P_f(x,z)\, w_r(x,z)\, dxdz = \Delta P_r(x,z)\, w_f(x,z)\, dxdz, \quad (1)$$

where V_f is a speed of direct flow and V_r ($V_r = V_f$) is a speed of reverse flow (Fig. 2), P is the pressure difference on upper and lower wing surfaces (aerodynamic load) while arbitrarily given distribution of downwash $\omega(x, z)$ (subscript f refers to the direct flow, r – to the reverse flow), integration is made on the wing surface S (Fig. 2). The equation (1) is valid in case of flow around a wing by ideal incompressible fluid, and also when an equation for the velocity potential is a linear in the exact formulation of a task or approximately.

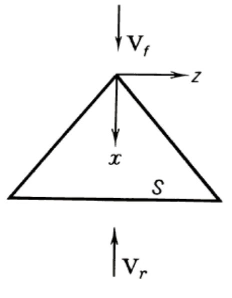


Fig. 2. The thin wing with direct and reverse streams

This theorem is approved by application of Green formula to this linear equation taking into account appropriate boundary conditions.

II. PROBLEM STATEMENT

From the RT it follows a series of consequences that simplify the calculation of operating on the wing aerodynamic forces and moments. According to one of them, the lifting force of the wing in direct flow has the same value as that in the reverse flow.

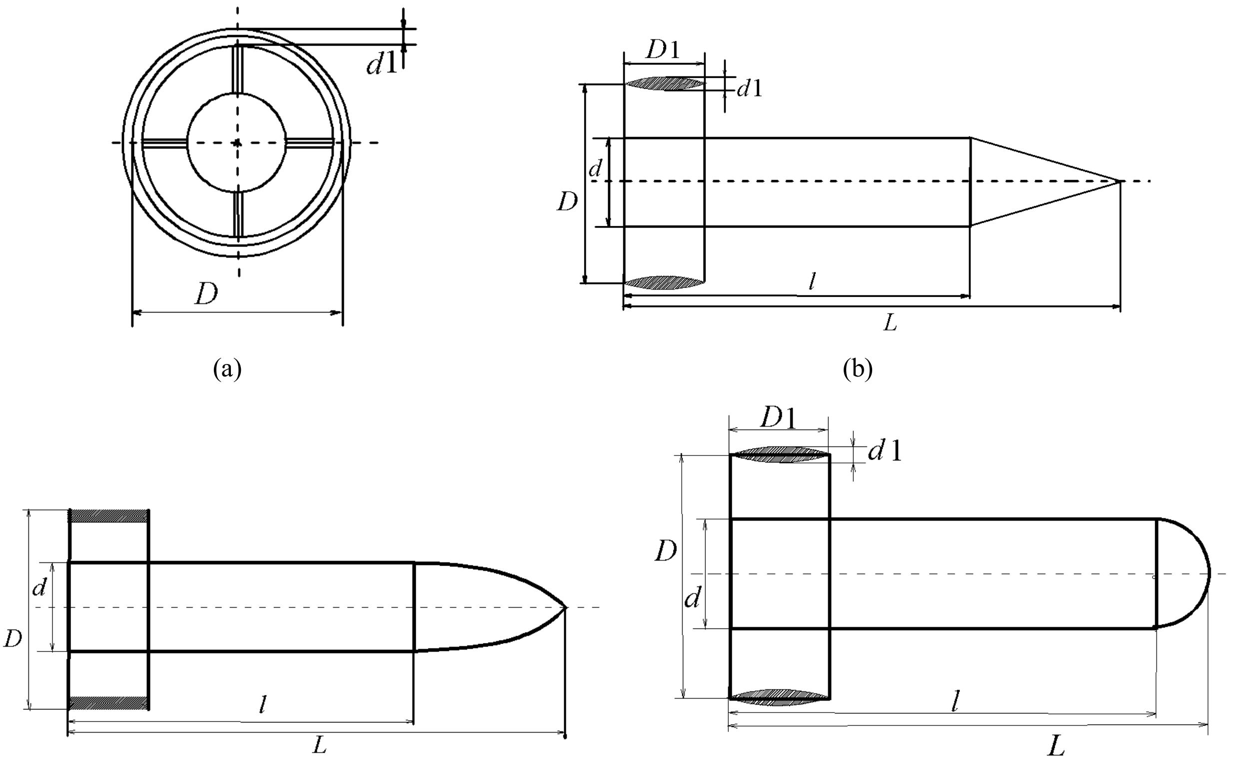
Another consequence relates to the calculation of aerodynamic forces and moments from the wing with a deformable surface or deflectable organs of control.

The aim of this work is the experimental checking of the first consequence of RT for an axially symmetric body with an empennage.

For this purpose wind tunnel tests with subsonic flow (velocity of flow letter or equal 50 m/s) are to be implemented. For the experiments three configurations of the fore body for an axially symmetric thin body were chosen. Besides, for these configurations of the fore body three types of wings were chosen: No.10 – monoplane; No.11 – annular wing; No.12 – latticed wings.

III. DESCRIPTION OF THE UAV MODELS AND EXPERIMENTAL RESULTS

The external appearance of UAV with an annular wing and different types of fore body is shown in Fig. 3.



(a) (b)

(c) (d)

Fig. 3. The external appearance of the forward part of UAV with an annular wing: (a) is the front view; (b), (c), and (d) is the side view: (b) is conical – No.1; (c) is ogival – No.2; (d) is hemisphere – No.3

Dimensions of UAV for Fig. 3,b are: length of UAV $L=10d$; diameter $D = 2d$; $d = 0.1$ m; $l = 8d$; $d1 = 0.1d$.

Dimensions of an axially symmetric thin body for other configurations of the forward part differed slightly.

The external appearance of UAV with wings “monoplane” is shown in Fig. 4. Dimensions of the monoplane wing are: $D = 3d$; $l2 = 1.1d$; $l1 = 0.5d$.

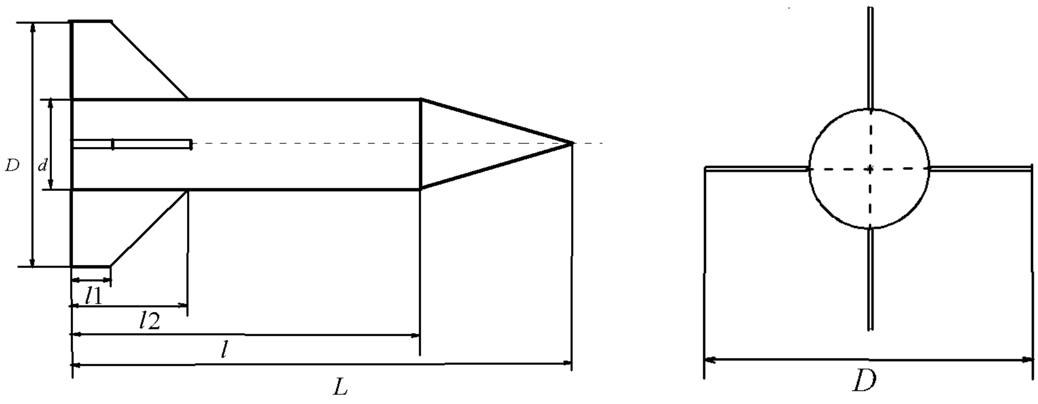
The external appearance of UAV with latticed wings is shown in Fig. 5. Dimensions of the latticed wing (Fig. 6) are: $D = 3.2d$; $l1 = 0.1d$, $d2 = 1.1d$, $d1 = d$. Dimension of the lattice is equal $d3 = 0.1d$.

At implementing of experiments, wind tunnel tests for direct and reverse streams were done for both isolated axially symmetric thin bodies and UAV models with wings. Results of comparison of the lift force coefficients for isolated axially symmetric thin bodies for direct and reverse streams are shown in Table I and in Fig. 7. As a numeric factor of RT execution it was chosen the value

$$E_{rel} = \frac{\left|C_{y-\exp} - C_{y+\exp}\right|}{C_{y+\exp}}, \qquad (2)$$

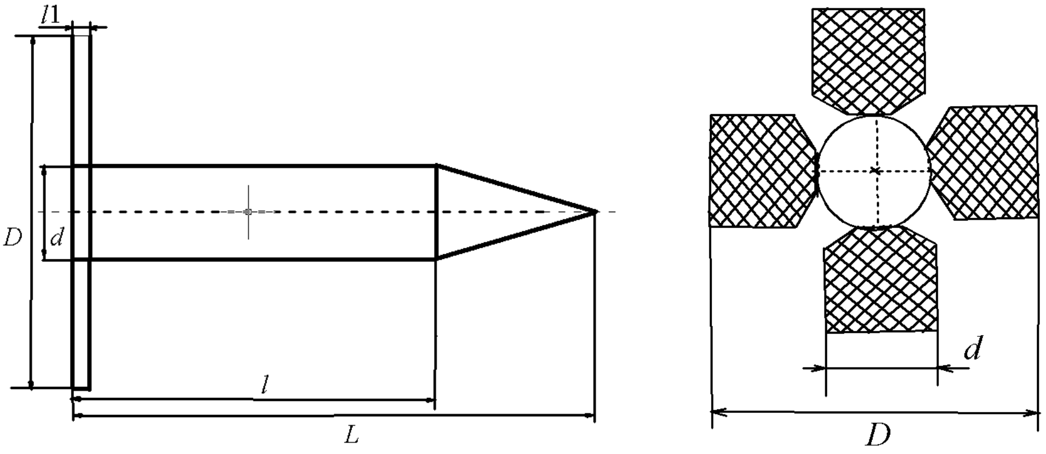
where $C_{y+\exp}$ are the lift force coefficients at direct direction of stream; $C_{y-\exp}$ are the lift force coefficients at inverse direction of stream.

Results of comparison of the lift force coefficients for the UAV ready-assembled for direct and reverse streams are shown in Table II and in Fig. 8.



(a) (b)

Fig. 4. The external appearance of UAV with wings “monoplane”: (a) is the side view; (b) is the front view



(a) (b)

Fig. 5. The external appearance of UAV with latticed wings: (a) is the side view; (b) is the front view

Comparison of experimentally obtained coefficients C_y for direct and reverse flow with their theoretical values is shown in Table III and Fig. 9, where as numeric factors of RT execution E_{rel1} (3) for direct flow and E_{rel2} (4) for inverse were chosen.

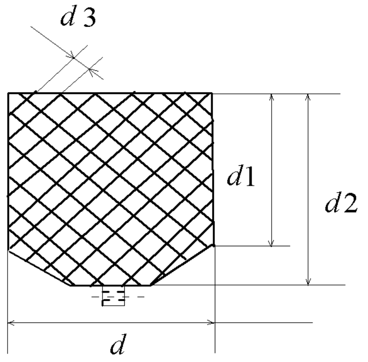


Fig. 6. The external appearance of a latticed wing

The expression of numeric factors of RT execution E_{rel1} and E_{rel2} are represented below:

$$E_{rel1}=\frac{\left|C_{xtheor}-C_{x+\exp}\right|}{C_{xtheor}}, \qquad (3)$$

$$E_{rel2}=\frac{\left|C_{xtheor}-C_{x-\exp.}\right|}{C_{xtheor}}. \qquad (4)$$

where C_{xtheor} is the calculated (theoretical) value of the drag force coefficient for the chosen model in the direct stream; $C_{x+\exp.}$ is the experimental value of the drag force coefficient for the chosen model in the direct stream; $C_{x-\exp.}$ is the experimental value of the drag force coefficient for the chosen model in the reverse stream.

TABLE I

RESULTS OF COMPARISON OF THE LIFT FORCE COEFFICIENTS FOR ISOLATED AXIALLY SYMMETRIC THIN BODIES FOR DIRECT AND REVERSE STREAMS

α, grad		5	10	15	20
$E_{rel}\times10^2$	No.1	12.5	10.2	8.1	3.0
	No.2	8.7	8.5	6.3	10.5
	No.3	12.4	4.7	3.7	3.2

TABLE II

RESULTS OF COMPARISON OF THE LIFT FORCE COEFFICIENTS FOR UAV MODELS FOR DIRECT AND REVERSE STREAMS

α, grad		5	10	15
$E_{rel}\times10^2$	No.1–10	6.3	6.0	6.6
	No.1–11	7.6	3.8	4.4
	No.1–12	12.5	7.5	2.5

TABLE III

RESULTS OF COMPARISON OF THE DRAG FORCE COEFFICIENTS FOR UAV MODEL NO.1 WITH WING "MONOPLANE" FOR DIRECT AND REVERSE STREAMS

α, grad	5	10	15	20
$C_{x+\mathrm{exp}}$	0.85	1.45	2.52	3.93
$C_{x\text{-}\mathrm{exp}}$	0.76	1.31	2.87	3.56
$C_{x\ theor.}$	0.85	1.41	2.3	3.57
$E_{rel1}\times10^2$	0	2.8	8.7	9.2
$E_{rel2}\times10^2$	11.7	7.6	1.3	0.3

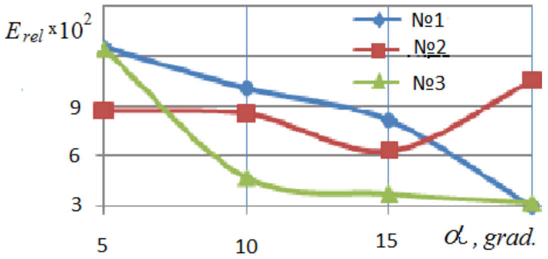


Fig. 7. Dependence of the numeric factor of RT execution for the different types of fore body from an angle α

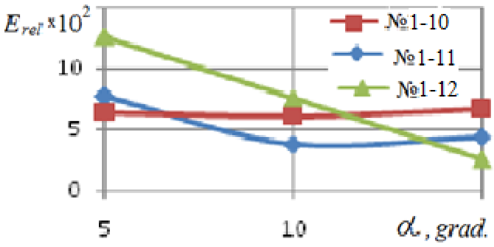


Fig. 8. Dependence of the numeric factor of RT execution for the UAV models from an angle α

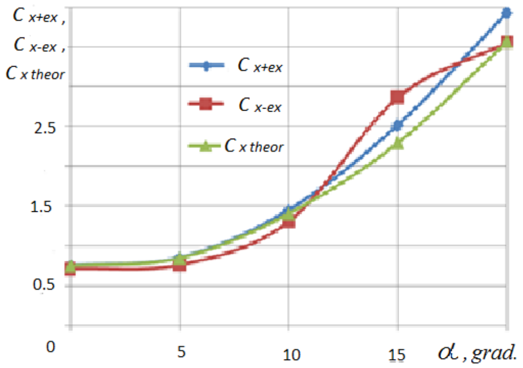


Fig. 9. Dependence of the drag force coefficients of the UAV for the direct and reverse streams from an angle α

Dependencies of the numeric factors E_{rel1} and E_{rel2} from an angle attack are shown in Fig. 10.

As follows from the analysis of the results of the experiments (see Figs 7 and 8), the smaller relative error is achieved at high angles of attack due to an increase of the absolute value of the lift force coefficient C_y, which is included in the denominator of the equation (2).

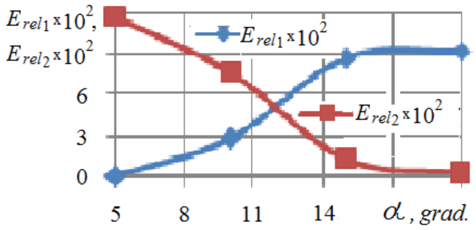


Fig. 10. Dependence of the numeric factors of RT execution E_{rel1} and E_{rel2} from an angle α

V. CONCLUSION

The accuracy of coincidence the main aerodynamic characteristics of the UAV, for forward and reverse flows, is determined in this article.

Wind tunnel tests for experimental verification of the RT for three various shapes of fore body for an axially symmetric thin body for direct and reverse streams were implemented. Besides, such tests were implemented for UAV models with three types of wings. Results of investigations showed that the error of execution RT consequence can achieve 12.5% at the range of angles of attack from 0 to 20° (accordingly, from 180° to 200°).

REFERENCES

[1] Clinton E. Brown, *The reversibility theorem for thin airfoils in subsonic and supersonic flow*, NACA Technical Report 986, US, Jan 01, 1950.

[2] V. G. Lebed, S. A. Kalkamanov, and E.Y. Ilenko, "Approximate methods of calculating the aerodynamic characteristics of the profile in the range of variation of the angle of attack from 0 to 360°." *Systems of information processing*, 2014, Issue no. 4 (120), pp. 36–39. (in Russian)

[3] N. F. Krasnov, *Basics of aerodynamic calculation. Aerodynamics bodies of rotation, bearing and control surfaces. Aerodynamics of aircraft*, Textbook for students of technical colleges, Moscow, Vyshaya shkola, 496 p., 1981. (in Russian)

[4] Magazine FLIGHT INTERNATIONAL, 24-30 September 1997, 18 p.

[5] L. K. Safronov, I. P. Smorodin, L. V. Kasatkin, G. G. Skotnikov, V. N. Tashkin, and V. M. Boburkov, "Aviation rocket with reverse launch equipped by elements for killing, which are formed at detonation," Patent RU № 55118 (2006.07.27). (in Russian)

[6] V. Markowski and K. Perov, *Soviet aircraft missiles "Air-air,"* Moscow, Publishing center "Eksprint", 120 p. (in Russian)

Received October 19, 2016

Tupitsin Nikolay. Candidate of Science (Engineering). Associate Professor.
Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Education: Moscow Phisics-thechnical Institute, Moscow, Russia (1975).
Research area: dynamic of flight, experimental methods of aerodynamic, aviation simulators.
Publication: 87.
E-mail: nift@mail.ru

Ziganshin Anwar. Assistant.
Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Education: Kazan Aviation Institute. Kazan, Russia (1978).
Research interests: computer aided design systems, numerical methods of aerodynamics, renewable sources of energy.
Publications: 10.
E-mail: anwarzihan@gmail.com

Stepanenko Illia. Master (Engineering).
Education: National Aviation University of Ukraine, Kyiv (2014).
Research area: computer-integrated manufacturing processes.
Publication: 7.
E-mail: STEPANENKO.iLay@gMaiL.com

М. Ф. Тупіцин, А. А. Зіганшин, І. О. Степаненко. Експериментальна перевірка теореми оборотності для осесиметричного тіла з оперенням

Проведено випробування в аеродинамічній трубі для експериментальної перевірки теореми оборотності для трьох різних форм носової частини осесиметричного тіла в прямому і зворотному потоках. Крім того, такі випробування проведено для моделей БПЛА з трьома типами крил. Результати досліджень показали, що помилка виконання слідства з теореми оборотності може досягати 12.5% у діапазоні кутів атаки від 0 до 20° (відповідно, від 180° до 200°).

Ключові слова: теорема оборотності; аеродинамічні профілі; прямі й зворотні потоки; аеродинамічні характеристики; аналіз (математика); дозвукові потоки; коефіцієнти опору і підйомної сили.

Тупіцин Микола Федорович. Кандидат технічних наук. Доцент.
Кафедра авіаційних комп’ютерно-інтегрованих комплексів, Національний авіаційний університет, Київ, Україна.
Освіта: Московський фізико-технічний інститут, Москва, Росія (1975).
Напрям наукової діяльності: динаміка польоту, експериментальні методи аеродинаміки.
Кількість публікацій: 87.
E-mail: nift@mail.ru

Зіганшин Анвар Абдуллович. Асистент.
Кафедра авіаційних комп’ютерно-інтегрованих комплексів, Національний авіаційний університет, Київ, Україна.
Освіта: Казанський авіаційний інститут. Казань, Росія (1978).
Напрям наукової діяльності: системи автоматизації проектувальних робіт, числові методи в аеродинаміці, поновлювальні джерела енергії.
Кількість публікацій: 10.
E-mail: anwarzihan@gmail.com

Степаненко Ілля Олександрович. Магістр.
Освіта: Національний авіаційний університет України, м. Київ 2014 рік.
Напрям наукової діяльності: комп'ютерно-інтегровані технологічні процеси.
Кількість публікацій: 7.
E-mail: STEPANENKO.iLay@gMaiL.com

Н. Ф. Тупицин, А.А. Зиганшин, И. С. Степаненко. Экспериментальная проверка теоремы обратимости для осесимметричного тела с оперением

Проведены испытания в аэродинамической трубе для экспериментальной проверки теоремы обратимости для трех различных форм носовой части осесимметричного тела в прямом и обратном потоках. Кроме того, такие испытания проведены для моделей БПЛА с тремя типами крыльев. Результаты исследований показали, что ошибка выполнения следствия из теоремы обратимости может достигать 12.5% в диапазоне углов атаки от 0 до 20° (соответственно, от 180° до 200°).

Ключевые слова: теорема обратимости; аэродинамические профили; прямые и обратные потоки; аэродинамические характеристики; анализ (математика); дозвуковые потоки; коэффициенты сопротивления и подъемной силы.

Тупицин Николай Федорович. Кандидат технических наук. Доцент.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Образование: Московский физико-технический институт, Москва, Россия (1975).
Направление научной деятельности: динамика полета, экспериментальные методы аэродинамики.
Количество публикаций: 87.

Зиганшин Анвар Абдуллович. Ассистент.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Образование: Казанский авиационный институт, Казань, Россия (1978).
Направление научной деятельности: системы автоматизированного проектирования, численные методы в аэродинамике, возобновляемые источники энергии.
Количество публикаций: 10.
E-mail: anwarzihan@gmail.com

Степаненко Илья Александрович. Магистр.
Образование: Национальный авиационный университет Украины, Киев (2014).
Направление научной деятельности: компьютерно-интегрированные технологические процессы.
Количество публикаций: 7.
E-mail: STEPANENKO.iLay@gMaiL.com