DOI: https://doi.org/10.37434/tpwj2025.07.06

RESEARCH OF THE EDDY-CURRENT RESONANCE METHOD FOR MEASURING THE THICKNESS OF THE CARBON FIBER REINFORCED PLASTIC LAYER ON METALLIC STRUCTURES

V.M. Uchanin[1], **O.G. Aleschenko**[1], **A. Savin**[2], **V.Ja. Derecha**[3]

[1]G.V. Karpenko Physico-Mechanical Institute of the NASU
5 Naukova Str., 79060, Lviv, Ukraine
[2]Nondestructive Testing Department,
National Institute of Research and Development for Technical Physics, Iasi, Romania
[3]SE "ANTONOV"
1 Mrija Str., 03062, Kyiv, Ukraine

ABSTRACT

The possibility of non-contact measurement of a carbon fiber reinforced plastic (CFRP) layer on structures made of non-magnetic aluminium alloy and ferromagnetic steel by the eddy current method was investigated. The research was carried out using flat specimens made of aluminium alloy D16T and ferromagnetic steel St20, on which a set of 1 mm thick flat plates made of CFRP were tightly laid. The number of the plates was varied to simulate the different thickness of CFRP layer. Parametric type eddy current probes (ECP) in the form of windings with 300 and 600 turns installed on an 8 mm diameter ferrite core were studied (magnetic permeability — 600). The ECP output voltages were investigated in the resonant mode at operating frequencies of 5, 8.5 and 20 kHz. The obtained dependences of voltage in the resonant circuit on the thickness of the CFRP layer became the basis for development of a device for non-contact measurement of the CFRP layer thickness on products made of aluminium alloys in the range of thicknesses up to 12 mm and ferromagnetic steel in the range of thicknesses up to 15 mm. The ability to measure the CFRP layer on metal structures is relevant not only for non-destructive inspection of their quality during production, but also for monitoring the integrity of such layered structures during their operation. Operational monitoring envisages preliminary determination of the thickness of CFRP layer in the reference points with the purpose of their further use as reference values. An increase in the results of measuring the thickness of the CFRP layer in the reference points during monitoring relative to the reference values will indicate the formation of delamination at the "metal–CFRP" boundary or between individual CFRP layers in operation.

KEYWORDS: carbon fiber reinforced plastic, aluminium alloy, ferromagnetic steel, eddy current probe, thickness measurement, resonant mode, operating frequency

INTRODUCTION

Composite materials (CM) are becoming widely applied for fabrication of the modern structures, in particular in the aviation and space industry, shipbuilding and automotive industry, which allows a significant reduction of the structure weight without loss of the load-carrying capacity and reliability and reducing the fuel consumption [1, 2]. CM began to be developed in the 50s of the previous century in order to replace the metal structural alloys. The main purpose consisted in combining two or more components with different physical properties to achieve characteristics, not inherent to each material separately. It should be noted that the scope of application of CM parts in the aviation and space industry is continuously increasing. In particular, at SC "Antonov" the CMs were used in the designs of the following aircraft: AN-26, AN-28, AN-32, AN-70, AN-71, AN-72, AN-74, AN-124 and AN-225 [3]. Famous leaders of aircraft manufacturing, such as Boeing, Airbus and Saab AB create aircraft, in which the quantity of CM of different types reaches 60 % by weight. A special place is occupied by fibrous CM, in which different matrices are used in combination with the fibrous filler. These could be fiberglass plastics, which can be considered dielectrics, as they are made of fiberglass and matrix based on epoxy resin. A widely used CM is the Carbon Fiber Reinforced Polymer (CFRP) Composite [4–6]. They can be multilayer with different orientation (for instance, 0°, 45°, 90°) of the carbon fibers in the different layers. CFRP is an almost ideal material for making aircraft as their strength is comparable with that of steel with the specific weight almost twice smaller than that of aviation aluminium alloys. The properties of such a multilayer structure are a combination of the high strength of the carbon fibers with the elasticity of the matrix filler. On the whole, CFRP have unique properties, to which, alongside the abovementioned ones, we can add a low coefficient of thermal expansion, high damping capacity and corrosion resistance [7]. CFRP also have a high cyclic loading resistance, but they perform better under one-dimensional loads. This, among other things, encourages combining CFRP with the traditional metals [8], as the aircraft structures are subject to more complex three-dimensional loading.

With wider acceptance of CM, the need for development of new NDT technologies is increased, as the currently available NDT methods and means do not always allow solving the respective complex of new tasks [9, 10]. NDT problems arise due to the diversity of damage and defects, which are inherent only to CM and which differ significantly from those characteristic for the traditional materials. Such characteristic CFRP defects include poor adhesion between the components, which leads to various types of delaminations, disturbance of fiber orientation in the different layers, etc.

On the whole, CFRP can be considered heterogeneous structures, which consist at least of two homogeneous components (carbon fibre and polymer matrix), having pronounced interfaces and differing essentially by their electrical and physical properties. As regards the eddy current method, it is important that the polymer matrix is a dielectric, and the carbon fiber has sufficiently high specific electrical conductivity (SEC). In addition, the CFRP fibrous structure creates different SEC in different directions, i.e. there exists at least uniaxial SEC anisotropy, which can differ in the different layers, because of the different direction of the carbon fibers. Here it is rational to use the approach proposed by us, which consists in introducing the notion of an effective medium for heterogeneous materials, the theory of properties of which is at the development stage. The effective medium approximation can be used for CFRP, when we will conditionally consider the heterogeneous material (CFRP) as a homogeneous (uniform) material with effective SEC, which depends on the quantitative composition of the components. It can be assumed that effective SEC, allowing for different SEC and anisotropy of SEC of the CFRP components, will be significantly greater than that of the polymer matrix, but smaller than for the carbon fiber. We used the effective medium approximation to study the possibility of determination of copper content in the copper ores, where the material heterogeneity is due to a low SEC of diorite (host rock) and chalcogenite (copper pyrite), which has much higher SEC [11]. We also used the notion of effective SEC for analysis of the influence of SEC anisotropy on the signal of eddy current probe (ECP) with circular windings [12]. The effective medium approach and the "effective coercive force" term were also used to study the parameters of the magnetic hysteresis loop of layered objects, consisting of layers with different magnetic characteristics [13].

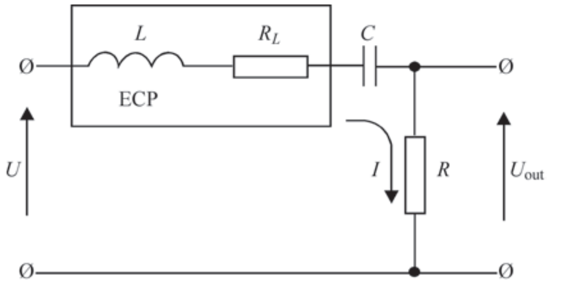

Figure 1. Schematic of connection of ECP of parametric type into the sequence oscillatory circuit

Lately there has been a problem of measuring the thickness of CFRP layer on metal structures, which is important not only for NDT of such layered structures in fabrication. A promising task is conducting the monitoring of CFRP integrity during the structure operation, which is related to the possible formation of delamination both at the CFRP interface with the metal base, and inside the CFRP. The known methods of measuring the CFRP thickness do not allow solving this problem. At first glance, the problem looks similar to that of measurement of the dielectric coating thickness. However, the known eddy current thickness meters for dielectric coatings are not suitable for measurement of CFRP thickness, because of its comparatively large SEC, and fast attenuation of the eddy currents at the used operating frequencies, respectively [14, 15]. The idea of solving the problem of measurement of a layer of metal-based CFRP consists in lowering the operating frequency, when the CFRP becomes "transparent" and its SEC will not have any significant influence on the depth of eddy current penetration.

THE OBJECTIVE

of the work is to study the possibility of measuring the CFRP thickness on structures and products from an aluminium alloy and ferromagnetic steel, based on application of ECP of parametric type in the resonant mode; determination of the optimal operating frequency and measurement range required for designing the appropriate instrument.

PARAMETERS OF THE STUDIED ECP, INVESTIGATION PROCEDURE, EXPERIMENTAL SPECIMENS

Investigations were performed using the resonant mode of eddy current testing, which envisages ECP connection into a series or parallel circuit with excitation from an external generator [1–17]. It is important that this allows separating the information component of the change in ECP impedance with tuning from the influence of uncontrolled parameter P_{ch}, which we will consider in the case of connecting the ECP into the series oscillatory circuit, the variant of which is given in Figure 1. The capacity and resistance of the resonant circuit are selected so that output voltage U_{out} did not depend on changes in uncontrolled parameter P_{ch}.

The diagram of the impedance of the operating circuit, when mounting the ECP on a non-magnetic tested object (TO) with certain initial values of ECP impedance parameters (point P_0) is given in Figure 2.

The diagram (Figure 2) shows the contribution of each of the components into formation of the vector of the impedance of the series circuit (points *A*, *B*, *C* and P_0). The values of resistance *R* and capacitance *C* of the capacitor, and its reactance, respectively, are selected such that the vector of impedance Z_0, formed the right angle with tangent *TT* to the line of influence of uncontrolled parameter P_{ch} in point P_0. In this case, change of parameter P_{ch} within certain limits (point *D*) practically does not cause any change in the module of the circuit impedance. At the same time, a change in the controlled parameter P_c (transition to point *E*) essentially influences its module. Under the condition of a constant amplitude of input voltage and parameters of the circuit elements, the output voltage amplitude is determined only by the module of the circuit impedance. Therefore it will change only slightly in case of changes in uncontrolled parameter P_{ch}, but at the same time it will significantly depend on controlled parameter P_c. Similar possibilities for tuning from the uncontrolled parameter can be also obtained with ECP connection into the parallel oscillatory circuit.

Two ECPs of parametric type were made for investigation: one with winding of 300 turns, wound with 0.09 mm wire, and the other with 600 turn winding. In both the ECPs the windings are mounted at the end of a ferrite core 8 mm in diameter and 40 mm long. The relative magnetic permeability of the core material is 600. The outer diameters of ECP windings are 9.5 and 11 mm, respectively, winding length is 8 mm. ECP inductances in case of their location in "air" (at a distance from the electrically conducting material) were equal to 5.2 mH (ECP with 300 turns) and 15 mH (ECP with 600 turns).

Investigations were conducted using a flat rectangular specimen 3 mm thick of 10x10 mm size from D16T aluminium alloy and a similar specimen 2 mm thick of carbon steel St20. During investigations the metal specimens were tightly packed into a set of flat plates from CFRP, which were provided by SC "ANTONOV". The thickness of each plate was 1 mm. The different thickness of CFRP layer was simulated by the different number of plates (from 1 to 15). Investigations of changes in output voltage of the resonant circuit with CFRP layer were conducted at operating frequencies of 5; 8.5 and 20 kHz. The influence of the thickness of CFRP layer on ferromagnetic steel St20 was studied at operating frequency of 5 kHz.

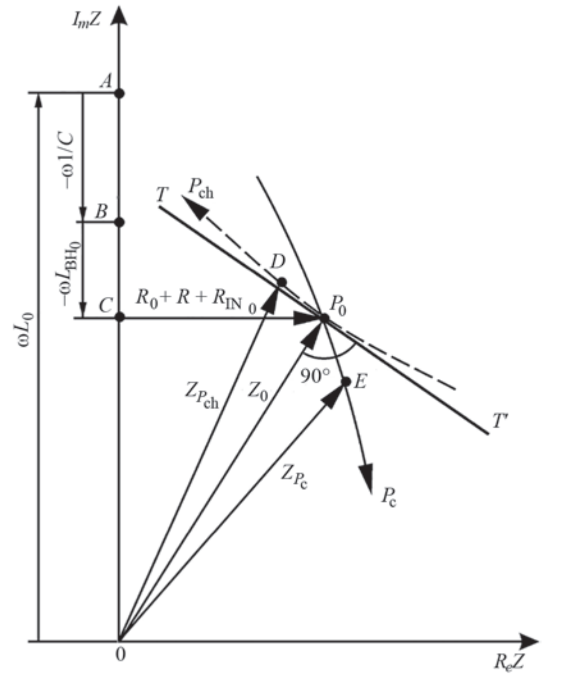

Figure 2. Influence of controlled P_c and uncontrolled P_{ch} parameter on the diagram of ECP complex resistances

ANALYSIS OF THE DERIVED RESULTS

Figure 3, *a* gives the dependence of output voltage *U* in the resonant circuit on thickness h_c of the CFRP layer on the metal specimen from aluminium alloy at operating frequencies of 5; 8.5 and 20 kHz. Figure 3, *b* gives the dependence of sensitivity S_{hc} of the output voltage on thickness h_c of CFRP layer, which was assessed as the difference of output voltage amplitudes with 1 mm increase in the thickness of CFRP layer in the different parts of the range.

The given results (Figure 3) demonstrate the fundamental possibility of measuring the thickness of CFRP layer in up to 12 mm range on structures from aluminium alloys by the eddy current method at the selected operating frequencies. The output voltage amplitudes are increased with increase in thickness h_c with the studied operating frequencies, asymptotically approaching the output voltage values during ECP placement "in air", which are equal to 3.27; 6.95 and 8.1 V for the operating frequencies of 5; 8.5 and 20 kHz, respectively. One can see that the rate of increase is inversely proportional to the value of thickness h_c of CFRP, which is confirmed by the respective dependencies of sensitivity S_{hc} in Figure 3, *b*, the shape of which can be considered close to the exponent. Here, at operating frequency of 20 kHz, the maximum changes in output voltage (from 4.29 to 8.04 V) have been obtained with increase in CFRP thickness from zero value to 12 mm. For smaller op-

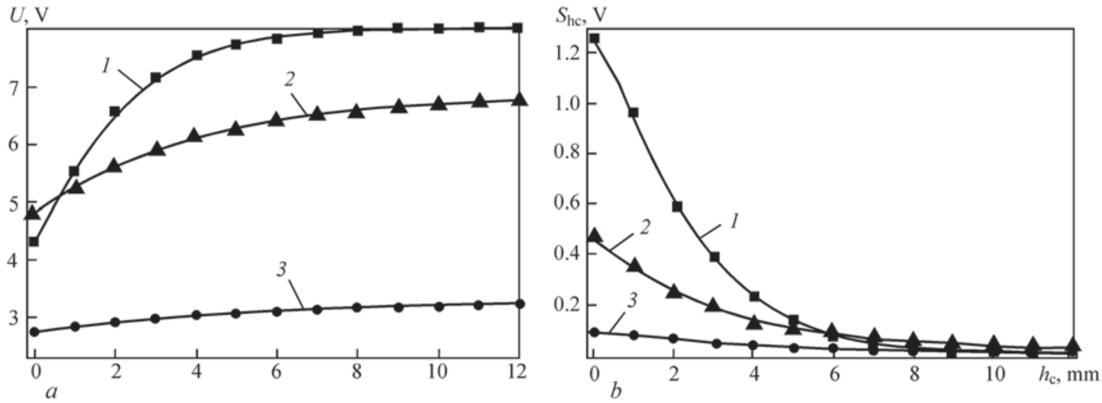

Figure 3. Dependence of output voltage U and respective dependencies of sensitivity S_{hc} on thickness h_c of CFRP layer for an aluminium alloy specimen at operating frequencies of: *1* — 20; *2* — 8.5, *3* — 5 kHz

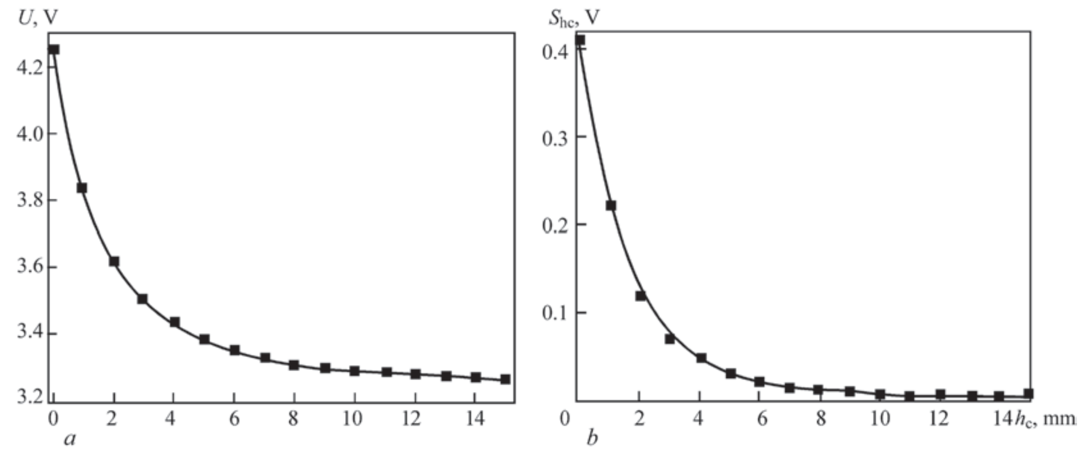

Figure 4. Dependence of output voltage U (*a*) and respective dependencies of sensitivity S_{hc} on thickness h_c of SFRP layer for a specimen from ferromagnetic steel St20 at operating frequency of 5 kHz

erating frequencies the respective voltage changes are significantly smaller: from 2.74 to 3.27 V at the frequency of 5 kHz and from 4.78 to 6.78 V at the frequency of 8.5 kHz. Thus, the operating frequency of 20 kHz can be considered optimal for measuring the CFRP thickness on aluminium alloy structures, the more so that the sensitivity at this operating frequency is the highest, particularly in the initial section in the range of changes in CFRP thickness.

Figure 4, *a* gives the dependence of output voltage U in the resonant circuit on thickness h_c of the CFPR layer on the specimen of St20 steel at operating frequency of 5 kHz, and Figure 4, *b* shows the respective dependence of sensitivity S_{hc} of output voltage on thickness h_c of CFRP layer on St20 steel.

The results given in Figure 4 also demonstrate the possibility of measurement of the thickness of CFRP layer on structures from ferromagnetic steel at operating frequency of 5 Hz. Here the possible range of measurement of CFRP thickness is up to 15 mm, which is attributable to a stronger influence of ferromagnetic steel on ECP inductance. One can see that the dependencies in Figure 3, *a* and Figure 4, *a* is symmetrical relative to the horizontal axis. However, unlike the previous dependencies for the non-magnetic aluminium alloy, here the output voltage amplitude decreases with increase of thickness h_c according to the law, close to the exponential one, asymptotically approaching the value of 3.25 V, corresponding to output voltage during ECP placement in "air". This is easily explained by the opposite influence of the non-magnetic and ferromagnetic metal on the change in ECP inductance. With ECP approaching the non-magnetic metal its inductance decreases, and, contrarily, ECP inductance increases at interaction with a ferromagnetic object. The rate of output voltage decrease is inversely proportional to the value of CFRP thickness h_c in the entire thickness range, which is confirmed by the respective curves of sensitivity S_{hc} in Figure 4, *b*. Let us recall that this property of proportionality between the rate of change of a quantity and the quantity proper is characteristics for an exponential dependence. It is obvious that such a non-linearity of the dependencies obtained in Figure 3, *a*, *b* should be taken into account during development of a resonant instrument for measurement of the thickness of CFRP layer on metal structures by introducing the linearization unit.

CONCLUSIONS

The eddy current method provides the possibility of non-contact measurement of the thickness of CFRP layer on metal structures from aluminium alloys in the thickness range of up to 12 mm and those from ferromagnetic steels in the thickness range of up to 15 mm. Derived dependencies of voltage in the resonant circuit on CFRP thickness will be used for development of an experimental specimen of a device for non-contact measurement of the thickness of CFRP layer on metal structures.

Measurement of the CFRP layer on metal structures is relevant not only for NDT of the quality of layered structure of "metal–CFRP" type in production. The authors proposed an approach for application of the developed method for monitoring the integrity of layered structures of "metal–CFRP" type during their operation, which envisages previous determination of the thickness of CFRP layer in the reference points for use as reference values. Increase in the results of measurement of the thickness of CFRP layer during operational monitoring in the reference points relative to the predetermined reference values will be indicative of formation of delaminations at the "metal–CFRP" interface or between the individual CFRP layers.

REFERENCES

1. Pezzuti, E., Donnici, G. (2014) Structural composites for aircraft design. *ARPN J. of Eng. and Applied Sci.*, 9(**10**), 1889–1898.
2. Kondratiev, A.V., Kovalenko, V.A. (2011) Review and analysis of world tendencies and problems of expansion of application of polymer composite materials in the units of rocket-space technology. *Collect. of Design and Production of Flying Vehicle Structures*, 3(**67**), 7–18. Kharkiv, KhAI [in Russian].
3. Kiva, D. (2014) Stages of formation and beginning of the deployed application of polymer composite materials in passenger and transport aircraft structures (1970–1995). *Aviatsyonno-Kosmicheskaia Tekhnika i Tekhnologiya*, **6**, 5–16 [in Russian].
4. Ozkan, D., Gok, M.S., Karaoglanli, A.C. (2020) Carbon fiber reinforced polymer (CFRP) composite materials, their characteristic properties, industrial application areas and their machinability. *Adv. Struct. Mater.,* **124**, 235–253. DOI: https://doi.org/10.1007/978-3-030-39062-4_20
5. Othman, R., Ismail, N.I., Pahmi, M.A.A.H. et al. (2018) Application of carbon fiber reinforced plastics in automotive industry: A review. *J. Mech. Manuf.*, **1**, 144–154.
6. Wisnom, M.R. (1992) On the high compressive strains achieved in bending tests on unidirectional carbon-fibre/epoxy. *Composites Sci. and Technol.*, 43(**3**), 229–235. DOI: https://doi. org/10.1016/0266-3538(92)90093-I
7. (2011) *Machining technology for composite materials: Principles and practice*. Ed. by H. Hocheng. Elsevier Science.
8. Pramanik, A., Basak, A., Dong, Y. et al. (2017) Joining of carbon fibre reinforced polymer (CFRP) composites and aluminium alloys — A review. Composites: Pt A: *Applied Science and Manufacturing,* **101**, 1–29. DOI: http://dx.doi.org/10.1016/j.compositesa.2017.06.007
9. Savin, A., Steigmann, R., Stanciu, M.D. et al. (2024) Evaluation of the mechanical characteristics of CFRP composites and modeling of the delamination phenomenon. *The Paton Welding J.*, **12**, 30–34. DOI: https://doi.org/10.37434/tpwj2024.12.05
10. Sharabura, O.M., Muravsky, L.I., Kuts, O.G. (2024) Detection of circular subsurface defects in laminated composites using optical-acoustic nondestructive testing system. *Tekh. Diahnost. ta Neruiniv. Kontrol*, **4**, 18–22 [in Ukrainian]. DOI: https://doi.org/10.37434/tdnk2024.04.03
11. Uchanin, V.M., Rybachuk, V.G. (2022) Possibility of eddy current testing of low-conductive heterogeneous media. *Vidbir ta Obrobka Informatsii,* 50(**126**), 5–12 [in Ukrainian]. DOI: https://doi. org/10.15407/vidbir2022.50.005
12. Rybachuk, V.H., Uchanin, V.M., Kulynych, Y.P. (2022) Specific features of testing of anisotropic nonmagnetic materials by eddy-current probes with circular windings. *Mater. Sci.,* **57**, 452–458 [in Russian]. DOI: https://doi.org/10.1007/s11003-022-00565-2
13. Rybachuk, V.G., Uchanin, V.M. (2023) A recurrent formula for determination of the effective coercive force in layered ferromagnetic materials. *Mater. Sci.,* **58**, 533–539. DOI: https://doi. org/10.1007/s11003-023-00695-1
14. Dorofeev, A.L., Nikitin, A.Y., Rubin, A.L. (1978) *Induction thickness measurement*. Moscow, Energiya [in Russian].
15. (1986) *Non-destructive testing of metals and products:* Handbook. Ed. by G.S. Samoilovich. Moscow, Mashinostroenie [in Russian].
16. Polulyakh, K.S. (1980) *Resonant measurement methods*. Moscow, Energiya [in Russian].
17. Arsh, E.I. (1979) *Autogenerator methods and measuring instruments*. Moscow, Mashinostroenie [in Russian].

ORCID

V.M. Uchanin: 0000-0001-9664-2101,
A. Savin: 0000-0001-9863-3110,
V.Ja. Derecha: 0000-0003-1773-912X

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

V.M. Uchanin
G.V. Karpenko Physico-Mechanical Institute of the NASU
5 Naukova Str., 79060, Lviv, Ukraine.
E-mail: vuchanin@gmail.com

SUGGESTED CITATION

V.M. Uchanin, O.G. Aleschenko, A. Savin, V.Ja. Derecha (2025) Research of the eddy-current resonance method for measuring the thickness of the carbon fiber reinforced plastic layer on metallic structures. *The Paton Welding J.*, **7**, 37–41.
DOI: https://doi.org/10.37434/tpwj2025.07.06

JOURNAL HOME PAGE

https://patonpublishinghouse.com/eng/journals/tpwj

Received: 07.04.2024
Received in revised form: 12.05.2024
Accepted: 09.07.2025