Вестник РУДН. Серия: Инженерные исследования
RUDN Journal of Engineering Research

2024;25(2):121–129

ISSN 2312-8143 (Print); ISSN 2312-8151 (Online)
journals.rudn.ru/engineering-researches

DOI: 10.22363/2312-8143-2024-25-2-121-129
UDC 621.91.01
EDN: HWEUSZ

Research article / Научная статья

Technical Solution to Decrease Cavitation Effects in the Kaplan Turbine Blade

Mohammed Ridha W. Khalid, Kazem Reza Kashyzadeh, Siamak Ghorbani✉

RUDN University, *Moscow, Russia*
✉ gorbani-s@rudn.ru

Article history
Received: December 7, 2023
Revised: March 21, 2024
Accepted: April 2, 2024

Conflicts of interest
The authors declare that there is no conflict of interest.

Authors' contribution
Undivided co-authorship.

Abstract. Application of Kaplan turbines is widespread in low-water-head and large-capacity hydropower plants. An understanding of the failure mechanism of Kaplan Turbines is a key factor to provide useful solutions for their prevention or early treatment and to guarantee their workability. The long-term performance of Kaplan turbines depends on many factors such as cavitation, erosion, fatigue, and material defects. Cavitation in Kaplan turbines leads to flow instability, vibrations, surface damage, and reduce the machine performance. Therefore, this paper investigates the factors leading to cavitation in Kaplan turbine and presents practical solutions for it. Thermal-sprayed coatings are frequently applied due to their high wear resistance, cost effectiveness, weight reduction, and less negative impacts on base metal. Moreover, HVOF is used to create coatings with a high density and bonding strength. At high temperatures, cermet coatings, including nanoparticles, exhibit exceptional wear resistance. WC-based nanostructured and multifaceted coatings are utilized due to their high wear resistance. In addition, chromium carbide in WC-based coatings increases their oxidation and wear resistance.

Keywords: kaplan turbines, cavitation, failure, HVOF, nanostructured coatings

For citation
Khalid MRW, Reza Kashyzadeh K, Ghorbani S. Technical solution to decrease cavitation effects in the Kaplan turbine blade. *RUDN Journal of Engineering Research.* 2024;25(2):121–129. http://doi.org/10.22363/2312-8143-2024-25-2-121-129

Техническое решение по снижению эффекта кавитации в лопатке турбины Каплана

М.Р.В. Халид, К. Реза Каши Заде, С. Горбани✉

Российский университет дружбы народов, *Москва, Россия*

✉ gorbani-s@rudn.ru

История статьи

Поступила в редакцию: 7 декабря 2023 г.
Доработана: 21 марта 2024 г.
Принята к публикации: 2 апреля 2024 г.

Заявление о конфликте интересов

Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов

Нераздельное соавторство.

Аннотация. Применение турбин Каплана широко распространено на гидроэлектростанциях малой и большой мощности. Понимание механизмов отказа указанных турбин является ключевым фактором для разработки решений по их предотвращению или своевременному устранению, а также для обеспечения их работоспособности. Надежная работа турбин Каплана зависит от многих факторов, таких как кавитация, эрозия, усталость и дефекты материалов. Кавитация в турбинах Каплана приводит к нестабильности потока, вибрациям, повреждению поверхности и снижению производительности машины. В связи с этим исследованы факторы, приводящие к кавитации в турбине Каплана, и представлены практические решения данной проблемы. Покрытия, нанесенные термонапылением, часто применяются из-за их высокой износостойкости, экономической эффективности, снижения веса и меньшего негативного воздействия на основной металл. Кроме того, высокоскоростное распыление кислородного топлива (HVOF) используется для создания покрытий с высокой плотностью и прочностью сцепления. При высоких температурах металлокерамические покрытия, в том числе наночастицы, обладают исключительной износостойкостью. Наноструктурированные и многогранные покрытия на основе WC используются из-за их высокой износостойкости. Кроме того, карбид хрома в покрытиях на основе WC повышает их стойкость к окислению и износу.

Ключевые слова: турбины Каплана, кавитация, отказ, HVOF, наноструктурированные покрытия

Для цитирования

Khalid M.R.W., Reza Kashyzadeh K., Ghorbani S. Technical solution to decrease cavitation effects in the Kaplan turbine blade // Вестник Российского университета дружбы народов. Серия: Инженерные исследования. 2024. Т. 25. № 2. С. 121–129. http://doi.org/10.22363/2312-8143-2024-25-2-121-129

Introduction

Kaplan turbines are used at sites with a typical head range of 2 to 40 meters, with 15–100% efficiency at full discharge of water [1]. The main problems in Kaplan hydro turbines are cavitation, erosion, fatigue, and material defects [2–4]. Hydraulic turbine deterioration is now largely due to cavitation, which decreases turbine efficiency, increases turbine vibrations, and blade wear, leading to reduce the turbine operating life [5; 6]. Xavier et al. have described cavitation as the state at which vapor cavities are created and expanded because of dynamic pressure reductions to the liquid's vapor pressure at constant temperature [7]. It is a fact that in order to increase energy production, turbines operate in ways that worsen the problem of cavity erosion [8]. Also, cavitation and other complex flow phenomena in the flow field leads to structural fatigue failures [9]. To promote research on cavitation in Kaplan hydro turbines, many scholars have summarized the related studies. Kjolle has discovered that the main causes of damage to water turbines is due to cavitation problems [10]. In this regard, runners and draft tube cones in Kaplan turbines are the turbine components most susceptible to cavitation. It has been stated that the impact of cavitation erosion may be lessened by enhancing hydraulic component production and design, using materials resistant to erosion, and positioning the turbines to operate within the permissible range of cavitation conditions [11]. The advantages of cavitation monitoring in hydraulic turbines through vibration methods have been demonstrated [12]. This method was applied to verify a small alteration to its distributor that aimed to decrease the severity of the cavitation and, consequently, the associated erosion. Karimi and Avellan have presented a new cavitation erosion device that generates vortex cavitation [13]. To confirm their vortex cavitation generator, a comparative research study between various cavitation erosion conditions was conducted. They concluded that the hardened surface layers in specimens exposed to flow cavitation were thicker than those in specimens exposed to vibratory cavitation, which results in faster rates of erosion. A hydro turbine blade online monitoring system has been implemented by Shi et al. [14]. In this research, Continuous Sound Monitoring (CSM) was done for both audible sound (20 Hz–20 kHz) and ultrasound (50–300 kHz). The signal properties were assessed, including the standard deviation, noise level, and frequency components. In addition, the evaluation results were stored in a database in association with the operating condition determined by the water head and wicket gate opening or power output. To this end, sound produced by cavitation was separated from other sounds like water flow and mechanical sound based on its frequency characteristics. Therefore, it was possible to determine the cavitation intensity at various water heads and powers. Alligne et al. have investigated the ability of hydroelectric power plants to adapt to changes in the use of electrical power networks [15]. Also, under specific circumstances, the swirling flow leaving the runner of a turbine may operate as an excitation source for the entire hydraulic system. The purpose of their study was to determine how the location of the full load excitation source affect the eigen values, shape modes, and the stability of the system. In summary, there is much research on different failure processes on the Kaplan turbine, which are the main reason for the authors of this paper to produce a state-of-the-art survey focusing on the cavitation problem alone to evaluate the current cavitation phenomenon for Kaplan turbine more effectively. Accordingly, the main aim of the present paper is to overview the Kaplan turbines' different failures based on the cavitation and introduce some practical solutions to reduce damages.

1. Cavitation phenomenon

Cavitation phenomenon is defined as the development of cavities (vapor bubbles) as a result of a pressure drop below saturated vapor pressure [16]. Kaplan turbine is prone to cavitation, which has the potential to reduce performance and harm the blade surfaces. Water vaporization and water vapor condensation are both involved in the two-phase (water and water-vapor) interaction known as cavitation. When the local pressure in the flow field is lower than the vapor pressure of water (e.g., 3.17 kPa at 25 °C), vapor bubbles are created [17]. Noise and vibrations are produced as a result of the high pressures that are briefly formed when the bubbles are compressed and collapsed. Industrial experience shows that vibrations and noise produced by cavitation cause cracks, particularly in Kaplan turbines [18]. Figure 1 presents examples of localized damage to a pump blade due to cavitation. Up to 90% of hydro turbines suffer cavitation damage, and cavitation-erosive damage is most likely to occur on the low-pressure side of the turbine runner blades [18]. The main types of cavitation in axial reaction turbines are tip vortex cavitation phenomena, lead edge cavitation, surface cavitation, hub cavitation, draft, and inter-blade vortex cavitation. In the following, a brief description of them will be given.

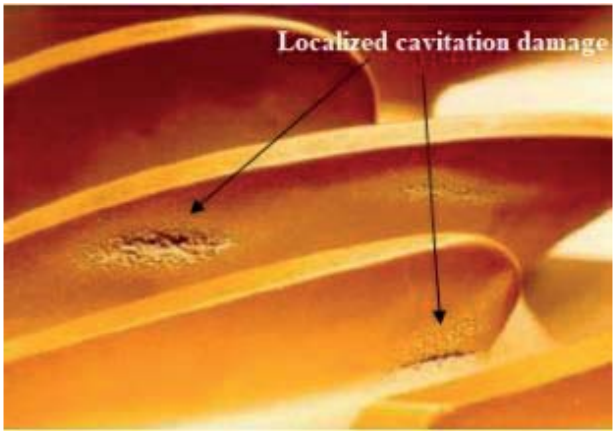


Figure 1. Localized cavitation damage and severe cavitation erosion on a pump blade
Source: Brennen C.E. [18]

1.1. Tip vortex cavitation

As shown in Figure 2, tip vortex cavitation can occur in the low-pressure sites generated over the turbine blades and in the wake of propellers and control surfaces [19]. When there are small bubbles or other cavitation nuclei in the core of a concentrated vortex and the core pressure shifts into tension, tip vortex cavitation begins to form. In the region of a vortex cavitation collapse, tip vortex cavitation may cause surface damage, noise, and a decrease in mechanical efficiency [20].

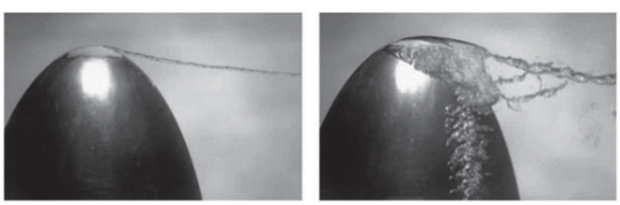


Figure 2. Cavitating tip vortices
Source: Higuchi H. et al. [19]

1.2. Lead edge cavitation

Attached cavitation, or leading-edge cavitation, is one of the cavitation categorizes that may form in a flow surrounding a lifting body and is known to cause significant erosive damage. From Figure 3, this kind of cavitation is distinguished by a partial vapor cavity that separates from a lifting body's leading edge and spreads downriver [21]. Also, due to operating at a higher head than the machine's design head, it manifests as a connected cavity on the suction side of the runner blades [11]. This is a very frequent and complex type of cavitation, and depending on the hydrodynamic circumstances, it can exhibit several regimes.

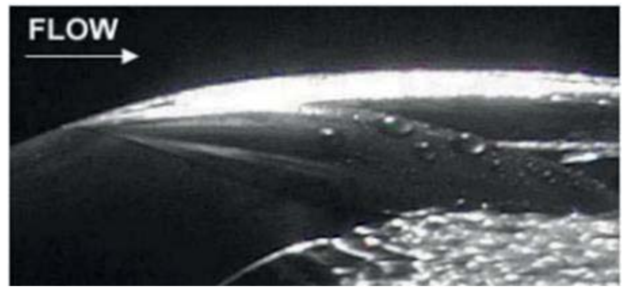


Figure 3. Lead edge cavitation
Source: Mohamed F., Francois A. [21]

1.3. Hub cavitation

The high swirl of the flow in the blade slipstream close to the rotational axis is where the wasted energy is first used up. This swirl will cause a pressure drop in relation to ambient pressure, which will produce an unfavorable drag force on the blade [22]. Also, when the swirl is high, axial thrust will not be produced by the energy transfer to the fluid at the hub, and turbulence will be dispersed by mixing. In addition, hub vortex cavitation, as shown in Figure 4, has a sizable cavity.

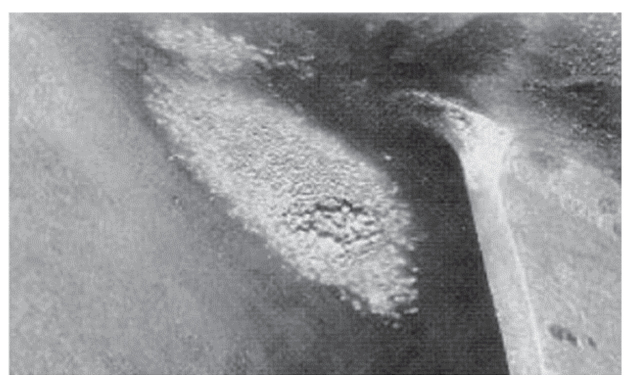


Figure 4. Hub vortex cavitation
Source: Sezen S., Atlar M. [22]

As a result, the lift force that is meant to be created may be lost if the rudder or any other control surfaces are positioned parallel to the propeller-shaft system axis. Eventually, depending on the axial load distribution on the propeller and hub geometry, the vortices around the hub cause an increase in energy loss, which lowers the propeller's efficiency. On the other hand, hub vortex cavitation may cause vibration, noise, and, in certain instances, surface erosion [23].

1.4. Traveling bubble cavitation

In this type of cavitation, the cavitation nuclei, also known as microbubbles, travel through the flow field until they reach the lower pressure zones, where they transform into large macroscopic cavitation bubbles before collapsing at pressure recovery zones. According to Figure 5, the interactions between the produced bubbles and nearby walls or other bubbles often result in complicated shapes for the bubbles [24].

Figure 5. Travelling bubble cavitation
Source: Jani D.B. et al. [24]

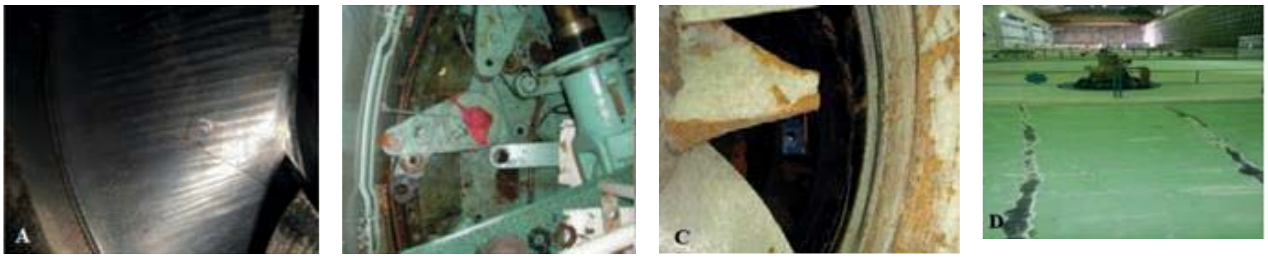
2. Cavitation measurement

In general, cavitation-erosion damage occurs in two stages: 1 — incubation stage, during which the surface deforms plastically but no weight loss is visible and is typically characterized by a duration or incubation period; 2 — erosion stage, during which weight loss and cracking occur at varying rates depending on the time [25]. The incubation period was first described by Leith as the time when significant plastic deformation of the test surface occurs without any visible weight loss [26]. Based on the maximum mean penetration rate, some researchers have developed relationships to estimate the incubation duration. In this regard, the volume loss in the sample divided by the exposed area yields the maximum depth of penetration. This criterion is very helpful for evaluating materials with varying densities and incubation times in various cavitation devices [26]. For materials that have been exposed to cavitation, residual stress measurements and information about early microcrack formation by employing X-ray analysis have been utilized to predict early weight loss [27]. X-ray photoelectron spectroscopy or hyper spectral photography can be used to identify the composition of surface materials and surface degradation [28]. An increase in the first subharmonic of the ultrasonic driving frequency indicates the start of cavitation. The beginning of instability in enormous bubbles just before they begin to collapse is the cause of this phenomenon [29]. The acoustic signs might be different since the measuring approach is based on detecting the bubble collapse inside the bulk liquid near a surface [30]. The CaviSensor and CaviMeterTM systems are two of the cavitation sensors developed by The National Physics Laboratory (NPL) in the United Kingdom [31]. A hydrophone device called the Hygea ultrasonic activity meter by ultrawave uses a 15 mm diameter probe to measure the frequency and acoustic pressure inside an ultrasonic bath [32]. With a straightforward display for ultrasonic frequency (5–50 kHz) and power (10–100%), this device is geared toward end users and is suitable for comparing measurements over time.

3. Effects of cavitation on other parts of system

The following measures to detect cavitation have been undertaken: vibration, pressure, acoustic emission, sound measurements [33]. Cavitation severely harms turbines by destroying the runners' and flow channels' surfaces. Moreover, noise generation is significantly increased by cavitation-induced vibration. In hydropower plants, equipment failure brought on by vibration results in shutdowns or a catastrophe [2; 34].

Excessive vibrations wear down components like guide vanes, runner blades, rims, bearings, shaft seals, and runner labyrinths through fatigue, as shown in Figure 6. Sometimes hydropower units are operated in the draft tube surge region to accommodate the various power systems. Draft tube vibrations also arise during remote operations of a unit with an operator in a surging region. The power plant operator can feel or hear some noise during this procedure, and as a result, it can take the necessary precautions to leave this dangerous zone.



a *b* *c* *d*

Figure 6. Failures due to excessive vibrations:
a — runner blade crack Kaplan turbine. S o u r c e : [35], *b* — breakage of wicket gate linkage. S o u r c e : [36];
c — runner blade damage. S o u r c e : made by G. Siamak, S. Ghorbani
d — structural cracks in Haditha hydropower plant. S o u r c e : photo by Ministry of Electricity of Iraq, https://mofa.gov.iq/geneva

4. Technical solution

Several techniques, including plasma nitriding, shot peening, deep rolling, and coating deposition, have been discussed to enhance cavitation erosion resistance by hardening the material's surface. The improvement depends on the substrate, coating material, and testing conditions, but even when these factors are the same, there are occasionally noticeable variances in the improvement [37]. Furthermore, a protective layer or coating component's production conditions may occasionally be slightly altered, which may even result in a reduction in resistance against untreated material. Plasma nitriding can increase resistance up to

20, but this is not uncommon. Also, up to five times more erosion resistance can be achieved with friction stir processing or shot peening [38]. When increased cavitation-erosion resistance is required, cobalt alloys are employed. Due to the development of an extremely tough, supersaturated fcc-phase known as expanded austenite, or S-phase, low-temperature plasma nitriding is known to signifycantly improve the CE resistance of austenitic and duplex stainless steels [38]. PVD coatings were one of the other efficient treatments (an improvement of up to 40 times) created from a very soft reflective coating to one that is extremely hard and resistant to fatigue even at high temperatures [39]. However, the majority of PVD coating applications are linked to their high hardness, elastic modulus, fracture strength, strong tribological properties-particularly low friction coefficient—good oxidation resistance, good fatigue endurance, and high wear resistance [40, 41]. Due to their greater hardness, fracture toughness, and subsequently increased wear resistance compared to their traditional counterparts, nanostructured WC-Co based thermal spray coatings have garnered considerable attention in recent years. The strong tendency of these coatings to decarburize and dissolve during the thermal spraying process, which can impair their mechanical qualities, has long been a challenge for nanostructured WC-Co-based coatings [42]. In addition, the results of studies showed that HVOF sprayed nanostructured WC-Co based coatings had higher wear, corrosion, and cavitation erosion resistance than conventional ones and were better bonded to the substrate with a high fraction of retained near-nano WC grain, low porosity, and a low quantity of harmful reaction products [43].

Conclusion

To increase the wear resistance of component surfaces, various techniques such as thermal spraying, plasma nitriding, chemical vapor deposition, physical vapor deposition, laser cladding, and hardening have been developed. Also, for different machinery components, thermal spraying techniques like Air Plasma Spraying (APS), Detonation Gun (D-Gun), and HVOF have been used. In hydro power plant facilities, where mechanical components are subjected to severe abrasive wear, HVOF spraying has been extensively utilized to apply WC-based coatings. Due to their exceptional resistance to abrasive wear, WC-based nanostructured and multifaceted coatings have received a lot of interest. By providing an efficient means of controlling processing variables during thermal spraying application, the WC-Co coatings produced by HVOF that contain nanoparticle sizes have better mechanical and tribological properties.

References

1. Gordon JL. Hydraulic turbine efficiency. *Canadian Journal of Civil Engineering*. 2001;28(2):238–253. https://doi.org/10.1139/l00-10

2. Fahmi ATWK, Kashyzadeh KR, Ghorbani S. A comprehensive review on mechanical failures cause vibration in the gas turbine of combined cycle power plants. *Engineering Failure Analysis.* 2022:106094. https://doi.org/10.1016/j.engfailanal.2022.106094

3. Kashyzadeh KR, Kivi SA, Rynkovskaya M. Fatigue life assessment of unidirectional fibrous composite centrifugal compressor impeller blades based on FEA. *International Journal of Emerging Technology and Advanced Engineering.* 2016;7:6–11.

4. Amiri N, Shaterabadi M, Reza Kashyzadeh K, Chizari M. A comprehensive review on design, monitoring, and failure in fixed offshore platforms. *Journal of Marine Science and Engineering.* 2021;9(12):1349. https://doi.org/10.3390/jmse9121349

5. Rus T, Dular M, Širok B, Hočevar M, Kern I. An Investigation of the Relationship Between Acoustic Emission, Vibration, Noise, and Cavitation Structures on a Kaplan Turbine. *Journal of Fluids Engineering.* 2007; 129(9):1112–1122. https://doi.org/10.1115/1.2754313

6. Cencîc T, Hocevar M, Sirok B. Study of Erosive Cavitation Detection in Pump Mode of Pump–Storage Hydropower Plant Prototype. *Journal of Fluids Engineering*. 2014;136(5):051301. https://doi.org/10.1115/1.4026476

7. Xavier E, Eduard E, Mohamed F, Francois A., Miguel C. Detection of cavitation in hydraulic turbines. *Mechanical Systems and Signal Processing.* 2006;20(4): 983–1007. https://doi.org/10.1016/j.ymssp.2004.08.006

8. Duraiselvam M, Galun R, Wesling V, Mordike BL, Reiter R, Oligmuller J. Cavitation erosion resistance of AISI 420 martensitic stainless steel laser-clad with nickel aluminide intermetallic composites and matrix composites with TiC reinforcement. *Surface and Coatings Technology*. 2006;201(3–4):1289–1295. https://doi.org/10.1016/j.surfcoat.2006.01.054

9. Farrahi GH, Chamani M, Kashyzadeh KR, Mostafazade A, Mahmoudi AH, Afshin H. Failure analysis of bolt connections in fired heater of a petrochemical unit. *Engineering Failure Analysis* 2018;92:327–342. https://doi.org/10.1016/j.engfailanal.2018.06.004

10. Ming Z, David V, Carme V, Mònica E, Eduard E. Failure investigation of a Kaplan turbine blade. *Engineering Failure Analysis* 2019;97:690–700. https://doi.org/10.1016/j.engfailanal.2019.01.056

11. Kumar P, Saini RP. Study of cavitation in hydro turbines — A review. *Renewable and Sustainable Energy Reviews.* 2010;14(1):374–383. https://doi.org/10.1016/j.rser.2009.07.024

12. Farhat M, Bourdon P, Gagné JL, Remillard L. Improving hydro turbine profitability by monitoring cavitation aggressiveness. *CEA Electricity '99 Conference and Exposition*. Vancouver, March. 1999. p. 1–15.

13. Karimi A, Avellan F. Comparison of erosion mechanisms in different types of cavitation. *Wear.* 1986; 113(3):305–322. https://doi.org/10.1016/0043-1648(86)90031-1

14. Shi H, Li Z, Bi Y. An On-line Cavitation Monitoring System for Large Kaplan Turbines. *2007 IEEE Power Engineering Society General Meeting.* Tampa, FL, USA; 2007. https://doi.org/10.1109/PES.2007.385723

15. Alligne S, Nicolet C, Allenbach P, Kawkabani B, Simond JJ, Avellan F. Influence of the vortex rope location of a Francis turbine on the hydraulic system stability. *Proceedings of the 24th Symposium on Hydraulic Machinery and Systems, Foz do Iguassu, Brazil, October 27–31, 2008.* http://doi.org/10.5293/IJFMS.2009.2.4.286

16. Mohammad DA, Frengki MF. Cavitation Analysis of Kaplan-Series Propeller: Effect of Pitch Ratio and nProp using CFD. *International Journal of Marine Engineering Innovation and Research*. 2021;6(2): 114–124. http:// doi.org/10.12962/j25481479.v6i2.8747

17. White FM, Majdalani J. *Viscous Fluid Flow.* 4th ed. New York, NY: McGraw-Hill Education; 2021. 2021.

18. Brennen CE. *Cavitation and bubble dynamics.* UK: Cambridge University Press; 2013.

19. Higuchi H, Arndt REA, Rogers MF. Characteristics of Tip Vortex Cavitation Noise. *Journal of Fluids Engineering*. 1989;111(4):495–501. https://doi.org/10.1115/1.3243674

20. Chang N,Ganesh H, Yakushiji R, Ceccio SL. Tip Vortex Cavitation Suppression by Active Mass Injection. *Journal of Fluids Engineering*. 2011;133(11):111301. https://doi.org/10.1115/1.4005138

21. Mohamed F, Francois A. On the detachment of a leading edge cavitation. *Laboratory For Hydraulic Machines Swiss Federal Institute of Technology EPFL-IMHEF-LMH*. Av. De Cour, 33 CH-1006 Lausanne, Switzerland. 2014. Available from: https://caltechconf.library.caltech.edu/130/ (accessed: 02.05.2023)

22. Sezen S, Atlar M. Mitigation of Hub Vortex Cavitation with Application of Roughness. *Journal of Marine Science and Engineering*. 2022;10:1426. https://doi.org/10.3390/jmse10101426

23. Ghassemi H, Mardan A, Ardeshir A. Numerical analysis of hub effect on hydrodynamic performance of propellers with inclusion of pbcf to equalize the induced velocity. *Polish Maritime Research*. 2012;19:17–24. https://doi.org/10.2478/v10012-012-0010-x

24. Jani DB, Mistry Y, Suthar M, Suthar A, Shah J, Patel P. An overview on cavitation in centrifugal pump. *International Journal of Innovative Research in Technology*. 2019;6(5):1–5.

25. Pohl M, Stella J. Quantitative CLSM roughness study on early cavitation-erosion damage. *Wear*. 2002;252(5–6):501–511. https://doi.org/10.1016/S0043-1648(02)00003-0

26. Leith WC. *Cavitation damage of metals. Doctoral thesis*. McGill University, Department of Mechanical Engineering; 1960.

27. Mathias M, Göcke A, Pohl M. The residual stress, texture and surface changes in steel induced by cavitation. *Wear*. 1991;150(1–2):11–20. https://doi.org/10.1016/0043-1648(91)90302-B

28. Ermolieff A, Amouroux A, Marthon S, Faviet JF, Peccoud L. XPS studies of contamination of reactor and silicon surfaces caused by reactive ion etching. *Semiconductor Science and Technology*. 1991;6(4):290–295. https://doi.org/10.1088/0268-1242/6/4/011

29. Santis DP, Sette D, Wanderlingh F. Cavitation Detection: The Use of the Subharmonics. *The Journal of the Acoustical Society of America*. 1967;42(2):514–516. https://doi.org/10.1121/1.1910611

30. Neppiras E. Measurement of acoustic cavitation. *IEEE Transactions on Sonics and Ultrasonics*. 1968;15(2):81–88. https://doi.org/10.1109/T-SU.1968.29452

31. Gyöngy M, Coussios CC. Passive cavitation mapping for localization and tracking of bubble dynamics. *The Journal of the Acoustical Society of America*. 2010;128(4):175–180. https://doi.org/10.1121/1.3467491

32. Verhaagen B, Fernández RD. Measuring cavitation and its cleaning effect. *Ultrasonics Sonochemistry*. 2016;29:619–628. https://doi.org/10.1016/j.ultsonch.2015.03.009

33. Čdina M. Detection of cavitation phenomenon in a centrifugal pump using audible sound. *Mechanical Systems and Signal Processing*. 2003;17(6):1335–1347. https://doi.org/10.1006/mssp.2002.1514

34. Nandi S, Toliyat HA, Xiaodong L. Condition monitoring and fault diagnosis of electrical motors- a review. *IEEE Transactions on Energy Conversion*. 2005;20(4):719–729. https://doi.org/10.1109/TEC.2005.847955

35. Zhang M, Valentín D, Valero C, Egusquiza M, Egusquiza E. Failure investigation of Kaplan turbine blade. *Engineering failure analysis*. 2019;97:690–700. https://doi.org/10.1016/j.engfailanal.2019.01.056

36. Mohanta RK, Chelliah TR, Allamsetty S, Akula A, Ghosh R. Sources of vibration and their treatment in hydro power stations-A review. *Engineering Science and Technology, an International Journal*. 2016;20(2):637–648. https://doi.org/10.1016/j.jestch.2016.11.004

37. Alicja KK. Degradation and Protection of Materials from Cavitation Erosion: A Review. *Materials*. 2023;16(5):2058. https://doi.org/10.3390/ma16052058

38. Kumar R, Bhandari S, Goyal A. Synergistic effect of $Al_2O_3TiO_2$ reinforcements on slurry erosion performance of nickel-based composite coatings. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*. 2017;232(8):974–986. https://doi.org/10.1177/1350650117736487

39. Romero MC, Tschiptschin AP, Scandian C. Low temperature plasma nitriding of a $Co_{30}Cr_{19}Fe$ alloy for improving cavitation erosion resistance. *Wear*. 2019;426–427:581–588. https://doi.org/10.1016/j.wear.2019.01.019

40. Inspektor A, Salvador PA. Architecture of PVD coatings for metalcutting applications: a review. *Surface and Coatings Technology*. 2014;257:138–153. https://doi.org/10.1016/j.surfcoat.2014.08.068

41. Andrievski RA. Nanostructured superhard films as typical nanomaterials. *Surface and Coatings Technology*. 2007;201:6112–6116. https://doi.org/10.1016/j.surfcoat.2006.08.119

42. Krella AK. Degradation of protective PVD coatings, In: *Handbook of Materials Failure Analysis with Case Studies from the Chemicals, Concrete, and Power Industries*. 1st ed. Makhlouf A.S.H., Mahmood A. Publisher: Elsevier; 2016. p. 411–440.

43. Basak AK, Celis JP, Vardavoulias M, Matteazzi P. Effect of nanostructuring and Al alloying on friction and wear behaviour of thermal sprayed WC-Co coatings. *Surface and Coatings Technology*. 2012;206:3508–3516. https://doi.org/10.1016/j.surfcoat.2012.02.030

About the authors

Mohammed Ridha W. Khalid, Ph.D. student, Department of Mechanical Engineering Technologies, Academy of Engineering, RUDN University, Moscow, Russia; ORCID: 0009-0009-0798-4317; E-mail: 1042218144@rudn.ru

Kazem Reza Kashyzadeh, Candidate of Technical Sciences, Professor, Department of Transport, Academy of Engineering, RUDN University, Moscow, Russia; ORCID: 0000-0003-0552-9950; E-mail: reza-kashi-zade-ka@rudn.ru

Siamak Ghorbani, Candidate of Technical Sciences, Associate Professor, Department of Mechanical Engineering Technologies, Academy of Engineering, RUDN University, Moscow, Russia; ORCID: 0000-0003-0251-3144; eLIBRARY SPIN-code: 8272-2337; E-mail: gorbani-s@rudn.ru

Сведения об авторах

Халид Мохаммед Рида Валид, аспирант базовой кафедры машиностроительных технологий, инженерная академия, Российский университет дружбы народов, Москва, Россия; ORCID: 0009-0009-0798-4317; E-mail: 1042218144@rudn.ru

Реза Каши Заде Казем, кандидат технических наук, профессор департамента транспорта, инженерная академия, Российский университет дружбы народов, Москва, Россия; ORCID: 0000-0003-0552-9950; E-mail: reza-kashi-zade-ka@rudn.ru

Горбани Сиамак, кандидат технических наук, доцент базовой кафедры машиностроительных технологий, инженерная академия, Российский университет дружбы народов, Москва, Россия; ORCID: 0000-0003-0251-3144; eLIBRARY SPIN-code: 8272-2337; E-mail: gorbani-s@rudn.ru