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Redundant constraints in diesel engines' mechanisms: a case study

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ABSTRACT

IMO Model Courses 7.04 and 7.02 for marine engineers' knowledge requires students to acquire competencies that relate to basic construction and operation principles of marine diesel parts, wear detection, maintenance, and repair. But achievement by students of special skills and competencies is usually clouded by misunderstanding relations between marine diesel parts construction, features of their assembling, operation, and maintenance conditions with their wear and failures. Among other issues these is the result of practical cases lack in general engineering disciplines content. The aim of article was to illuminate used in Kherson State Maritime Academy (KSMA), case-study and authors practical experience based approach of general and specific knowledge mutual integration in studying «Machines and Mechanisms Theory», «Applied Mechanics», «Marine internal combustion engines» and «Marine Machinery Maintenance and Repair» academic disciplines. Presented in article results made it possible to enhance the achievement of special skills and competencies by future marine engineers.

1. Introduction.

The use of real world examples is widespread in mathematics education, physics, chemistry, electric engineering and marine energetics education, with the objective of increasing students' interest and promoting effective learning [3], [5], [7], [8] («When studying the science, the examples are more useful than the rules» - Isaac Newton).

Case-study approach makes possible for students and recent graduates to achieve new understandings from bringing them real-life experiences in civil, thermal, electric and mechanical engineering [2], because it provides a glimpse of how real-world engineering differs from traditional textbook problems and how engineering can impact on corporate bottom line. In basic engineering courses, studied in undergraduate the teaching process is important as studies objects will be used as a carrier to pull teaching along [14].

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2. Literature review and problem statement.

Students' interest in learning and future practicing in specific field by increasing gradually and systematically their engineering practice ability usually reach exactly in basic engineering education. Marine engineers tutoring, judging by the authors practice in KSMA, have a few specific options. From the one hand the lack of students' interest in some complicated chapters of «Applied Mechanics» academic discipline, for example topic «Redundant constraints in mechanisms», have a reason in absence in common handbooks [1], [4], [13] detailed practical cases related to marine machinery structure and operation, to illustrate the impact of redundant constraints on the life cycle of marine machinery. Therefore it is common for educators to use well-studied examples for railway transport, metallurgical and other non-marine machinery that additionally decreases students' interest. From the other hand, IMO Model Courses 7.04 and 7.02 for marine engineers learning require students to acquire competencies that relate to basic construction and operation principles of marine diesel parts, wear detection, maintenance, and repair. Some of those are shown in table 1. Shown there content of the IMO Model Courses does not regulate understanding by students relations between marine diesel parts construction, features of their assembling operation, and maintenance conditions with their wear and failures, but this understanding is the way to enhance the achievement of special skills and competencies. Authors convinced that providing during studying general and specific knowledge mutual integration and intersubject interrelations could make a synergetic effect and deepen understanding by students both of general and specific knowledge, namely load transfer and failure emergence processes which take place in marine machinery elements while assembling and operating.

Table 1: IMO Model Courses 7.04 and 7.02 content (excerpt).

IMO model course	7.04 OFFICER IN CHARGE OF AN ENGINEERING WATCH	
Function	1. Marine Engineering at the Operational Level.	3. Maintenance and Repair at the Operational Level.
Competence	1.4 Operate main and auxiliary machinery and associated control systems.	3.2 Maintenance and repair of shipboard machinery and equipment.
Knowledge, understanding and proficiency	1.4.1 Basic construction and operation principles of machinery systems / 1.4.1.1 Diesel engine.	3.2.3 Maintenance and repair such as dismantling, adjustment and reassembling of machinery and equipment / 3.2.3.8 Diesel engine.
Competence demonstration methods	- Name the materials used in the manufacture of the listed items, then describe, with the aid of sketches, the assembled construction of these items: - *a cylinder liner; - a piston; - a connecting rod; - a piston pin; - the crankshaft.* - Uses engine builders' manuals to obtain working clearances specified by the instructor.	- Dismantles and inspects all parts for wear and deterioration, including: *– pistons; – liners; – bearings.*
IMO model course	7.02 CHIEF ENGINEER OFFICER AND SECOND ENGINEER OFFICER	
Function	1. Marine Engineering at the Management Level.	
Competence	1.1 Manage the operation of propulsion plant machinery.	
Knowledge, understanding and proficiency	1.1.1 Design features, and operative mechanism of marine diesel engine and associated auxiliaries.	
Competence demonstration methods	Describes with the aid of sketches/computer aided drawing, material selection, and design features of the combustion chamber components of diesel engine: *- piston assembly.*	

Source: Authors.

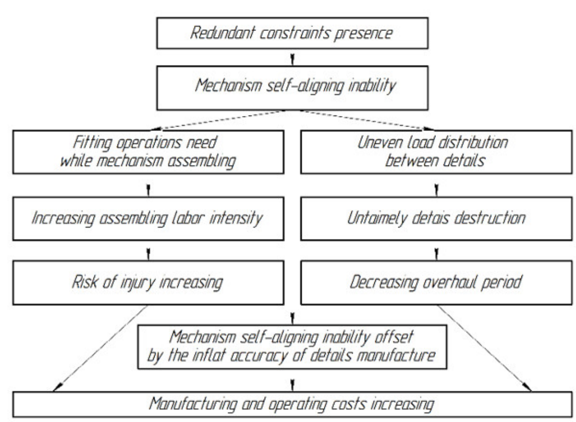
The main hypothesis of this work is that «Applied Mechanics» discipline «Redundant constraints in mechanisms» topic content extending by considering practice features of marine equipment (namely marine diesel engines) design, failures and assembling features is the way of future marine engineers specific professional skills and competencies achievement intensifying. The main aims of the work are:

- to analyze the common failure of marine trunk-type diesel rod bearings failures;
- to show redundant constraints impact on it, and elimination measures through diesel parts modifying that took place in practice;
- to show that extending "Applied Mechanics" content by including mentioned examples could intensify achievement of specific professional skills and competencies by students of marine engineering specialties.

3. Materials and methods.

Described circumstances encouraged authors to use of the case-study method because it allows combining theory and complex reality in the classroom. The use of the case-study method allows students to apply the acquired knowledge to solve specific practical problems and develops the ability to acquire competence [8], [14]. To provide this method in practice it was necessary to consider and analyze specific cases of diesel elements failures that have occurred in practice and analyze it, using specific machine and mechanism theory tools, to provide than an understanding of the impact of the presence of the redundant constraint in the mechanisms on the life cycle of the machine (fig. 1), and arouse students' interest in the professional specific disciplines study in senior courses. Moreover, detection and elimination of redundant constraints for the marine diesels' mechanisms is interesting because it is most common marine engines and especially acute because they contain multi-supported shafts, links which are intake in several kinematic pairs.

Figure 1: Redundant constraints influence on machine life cycle scheme.



Source: Authors.

4. Development.

4.1. Parts failures.

Main part of marine trunk-type diesels details (crankshafts, pistons, bearings) failures has their reason presence of misalignment while operation. In diesels, where piston connected with rod by cylindrical joint, most common of connection rod bearings failures (fig. 4) are: metal to metal contact (fig. 4, a); fatigue of outer-surface lining (fig. 4, b). Reducing the probability of the described failures is provide on practice maintenance by performing fitting operations while assembling, namely clearances $g_1 ... g_4$ measuring and additional tooling of connection rod bearings. The need to perform fitting operations is due to the mechanism links self-aligning inability because of redundant constraints presence.

4.2. Causes of failure.

Trunk-type diesel slider-crank mechanism contains three ($n = 3$) movable links - crankshaft 1, connection rod 2 and piston 3. Number of 5-class kinematic pairs here is $P_5 = 2$ (O_5, B_5), number of 4-class kinematic pairs is $P_4 = 2$ (A_4, C_4), pairs of third, second and first class are absent ($P_3 = P_2 = P_1 = 0$).

Total kinematic pairs number is:

$$P = P_5 + P_4 + P_3 + P_2 + P_1 = 2 + 2 + 0 + 0 + 0 = 4 \quad (1)$$

The sum of kinematic pairs movabilities:

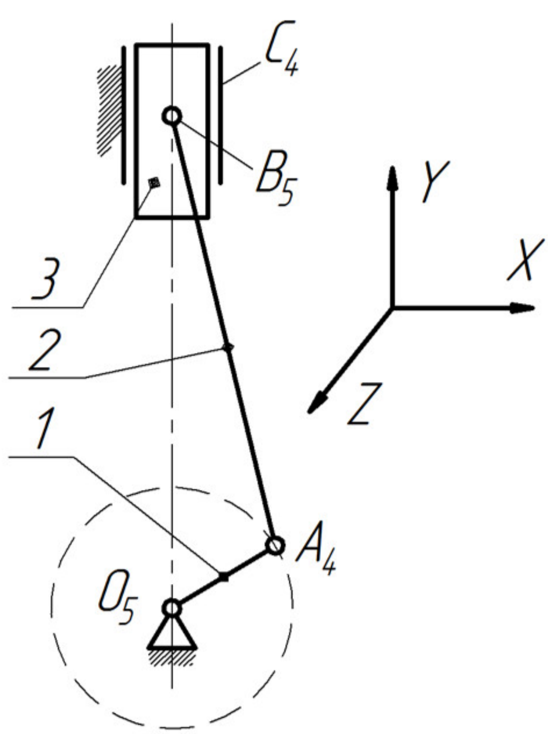
$$f = 1P_5 + 2P_4 + 3P_3 + 4P_2 + 5P_1 = \\ 1 \times 2 + 2 \times 2 + 3 \times 0 + 4 \times 0 + 5 \times 0 = 6. \quad (2)$$

Number of independent locked circuits by Gohman formula [13] is:

$$k = P - n = 4 - 3 = 1 \quad (3)$$

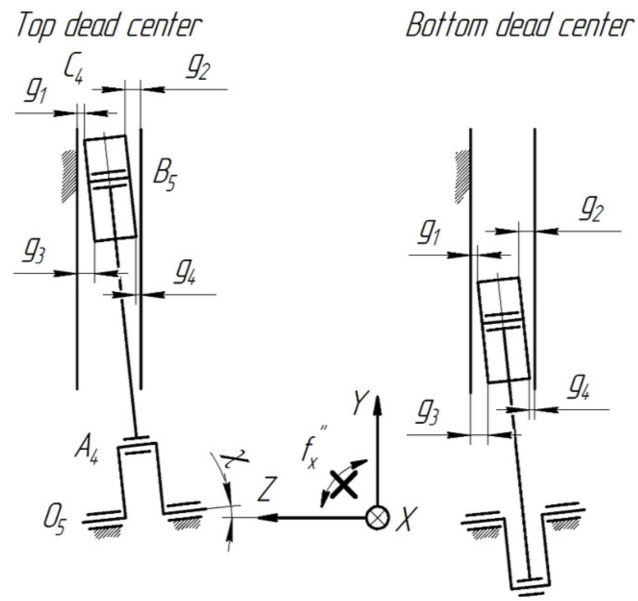
Single independent locked circuit in mechanism - $O_5A_4B_5C_4O_5$.

Figure 2: Structural diagram of slider-crank mechanism with piston and rod cylindrical connection.



Source: Authors.

Figure 3: Piston-cylinder liner clearances distribution diagram in slider-crank mechanism with piston and rod cylindrical connection in angular misalignment χ condition.



Source: Authors.

Total mechanism mobility by Voinea and Atanasiu [17] is:

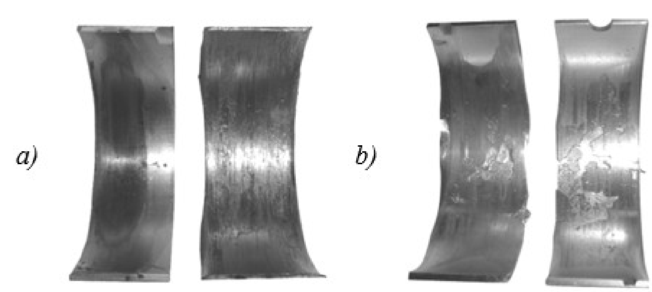
$$W = f - \sum r_i = 6 - 5 = 1 \quad (4)$$

where $r_1 = 5$ – independent locked circuit $O_5A_4B_5C_4O_5$ kinematic pairs axes rank.

Single mechanism mobility is its basic mobility $W = W_b$.

$$f = 1P_5 + 2P_4 + 3P_3 + 4P_2 + 5P_1 = \\ 1 \times 1 + 2 \times 2 + 3 \times 1 + 4 \times 0 + 5 \times 0 = 8. \quad (5)$$

Figure 4: Photographs of marine diesel engine misalignment-reasoned connecting rod bearings failures: metal to metal contact (a); fatigue of outer-surface lining (b).



Source: substech.com.

Redundant constraints number by Somov and Malyshev formula [13]:

$$q_{SM} = W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n = \\ 1 + 5 \times 2 + 4 \times 2 + 3 \times 0 + 2 \times 0 + 0 - 6 \times 3 = 1. \quad (6)$$

Circuit Reshetov's method [13] confirms given results and allows to specify redundant constraints type and location (table 2). Single angular redundant constraint q_1 in mechanism made impossible mechanism self-alignment due to movability around X-axe ($f_x^{''} = 0$) inability and causes uneven gaps $g_1 ... g_4$ (fig. 3) distribution which in practice compensating through additional tooling of connection rod bearings.

4.3. Failure elimination measures.

Liquidation of existing redundant constraint is possible by addition in circuit mobility around X-axe due to kinematic pairs class change. The easiest way to do it is connecting piston and rod by spherical joint. In this case class of B kinematic pair became third from fifth (fig. 5). Therefore, number of 5-class kinematic pairs became $P_5 = 1$ (O_5), number of 4-class kinematic pairs - $P_4 = 2$ (A_4, C_4), 3-class $P_3 = 1$ (B_3), second and first class $P_2 = P_1 = 0$.

The sum of kinematic pairs movabilities:

Total mechanism mobility:

$$W = f - \sum r_i = 8 - 6 = 2 \quad (7)$$

where $r_1 = 6$ – independent locked circuit $O_5A_4B_3C_4O_5$ kinematic pairs axes rank.

Total mechanism mobility including basic mobility $W_b = 1$ and piston 3 local mobility $W_l = 1$ (rotation around Y-axe) - $W = W_b + W_l = 2$.

Table 2: Circuit method application to slider-crank mechanism with cylindrical piston and rod connection.

Circuit	Planar movabilities f_n	Non-planar movabilities $f_н$
	$f_x^{'}$ $f_y^{'}$ $f_z^{''}$	$f_x^{''}$ $f_y^{''}$ $f_z^{'}$
$O_5A_4B_5C_4O_5$	Ø C B ↑W_b OA	Ø C A ↓q_1
$W = 1$, $q = 1$		

Source: Authors.

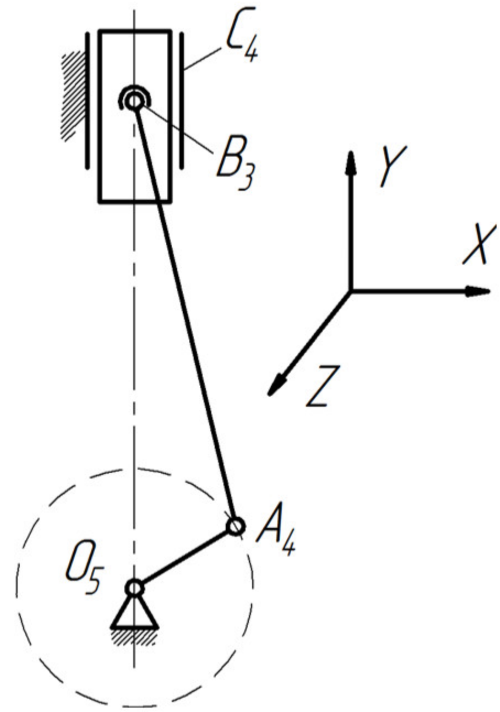
Redundant constraints number is:

$$q_{SM} = W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n = 2 + 5 \times 1 + 4 \times 2 + 3 \times 1 + 2 \times 0 + 0 - 6 \times 3 = 0. \quad (8)$$

$$q_{OZ} = W + 6k - f = 2 + 6 \times 1 - 8 = 0. \quad (9)$$

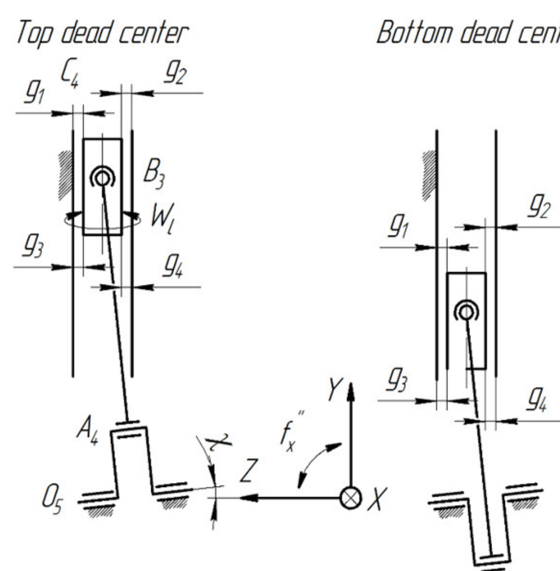
Circuit method confirms given results (table 3).

Figure 5: Structural diagram of slider-crank mechanism with piston and rod spherical connection.



Source: Authors.

Figure 6: Piston-cylinder liner clearances distribution diagram in slider-crank mechanism with piston and rod spherical connection in angular misalignment χ condition.



Source: Authors.

Making kinematic pair B spherical through adding $f_x^{''}$ movability, provides piston self-aligning on cylinder liner in angular misalignment χ condition. This became the reason of gaps $g_1 ... g_4$ alignment (fig. 6) while diesel assembling and operation and ensure even load distribution on connection rod bearing A

(fig. 7, b) compared with basic cylindrical joint (fig. 7, a). Piston and rod spherical connection realized in Sulzer ZA40-type (fig. 8) marine diesels. Existence in its mechanisms piston local movability W_l around own axe makes possible, due to ratchet mechanism, to provide piston rotation during engine operation [15], [18].

Table 3: Circuit method application to slider-crank mechanism with spherical piston and rod connection.

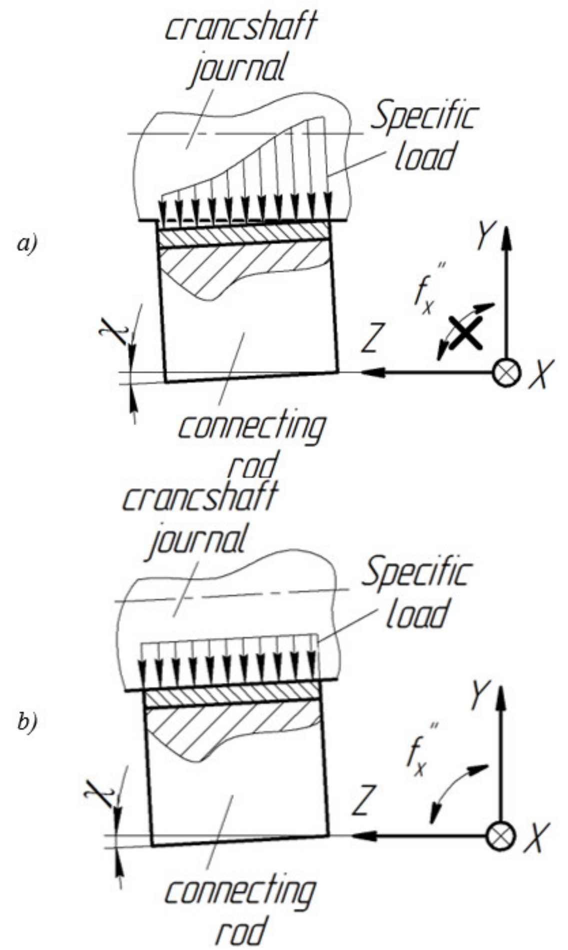
Circuit	Planar movabilities $f_п$	Non-planar movabilities $f_н$
	f_x' f_y' f_z''	f_x'' f_y'' f_z'
$O_5A_4B_3C_4O_5$	Ø C B OA W_b	B BC W_l A
$W = 2,\ q = 0$		

Source: Authors.

Providing links self-aligning possibility and piston local movability in Sulzer ZA40-type diesel slider-crank mechanism in operation gave following merits:

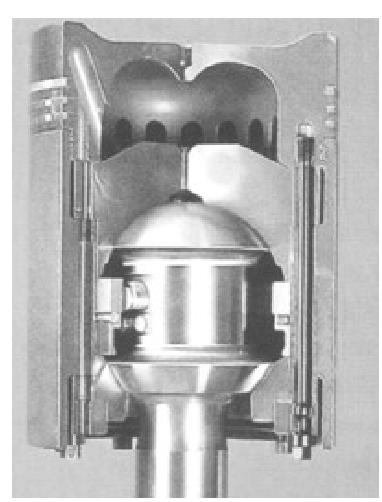
- eliminate the need for fitting operations work while diesel assembling and reduce the time for its maintenance and repair;
- even temperature distribution around the piston crown as there are no particular inlet and outlet zones;
- optimum sealing and working conditions for the piston rings because the small, symmetrical deformations of the piston allow the use of the smallest running gap between piston and cylinder liner;
- low and stable lubrication oil consumption because the small piston running gaps minimize piston slap and obviate the need for the traditional oil cushion, thereby allowing the oil scraper ring to be located at the lower end of the piston skirt;
- good margin for unfavorable running conditions with the smallest risk of seizure because the grey-iron piston skirt is always turning to a fresh part of the cylinder liner surface.

Figure 7: Connecting rod bearing load distribution diagram in the cylindrical (?) and spherical (b) piston and rod in angular misalignment χ condition.



Source: Authors.

Figure 8: Photograph Sulzer ZA40 engine's piston and rod spherical connection in section.

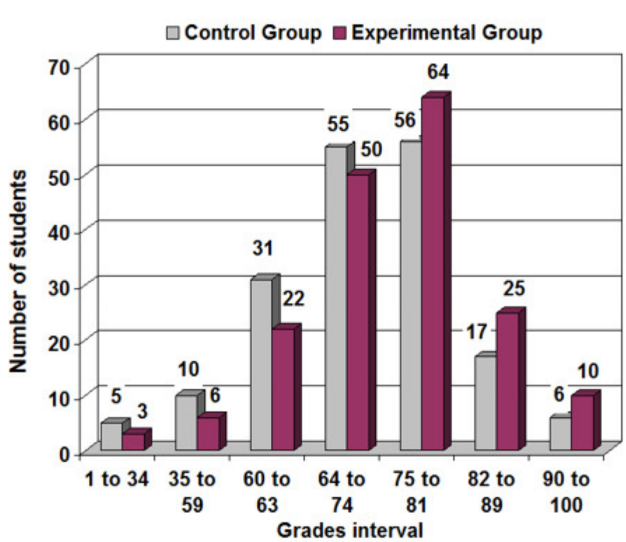


Source: Sulzer Brothers limited.

5. Results.

Using developed by the authors and presented in this paper issues in teaching the "Applied Mechanics" and «Machines and Mechanisms Theory» disciplines for students majoring in "Ship power plants operation" in KSMA continued in 2016-2020. Experimental evaluation of academic progress was done for 12 academic groups of students (total 360 persons) which were divided into two experimental groups - control and experimental. In the control group "Redundant constraints in mechanisms" section of "Applied Mechanics" discipline (4-th semester) was studied in a regular way using typical "non-marine" examples from widespread textbooks. In the experimental group, we used presented in this paper (and also in [11] and [12]) examples from our engineering practice. Studying theme "Redundant constraints in mechanisms" began there from trunk-type diesel elements failure analysis. After that we used to ask the audience a few questions - why is this happening? How to prevent this? What constructive decisions had to be made to avoid those failures? How do redundant constraints influence marine diesel slider-crank mechanism maintenance features? How do diesel elements construction effect on load distribution between them and their failures? These questions were answered during the classwork, performing a structural analysis of the mechanisms, finding the number and location of redundant constraints, and suggesting options for their elimination. Then, a comparative analysis of students' learning of topics "Diesels movement parts design" and "Diesels movement parts maintenance and repair" of disciplines, respectively "Marine internal combustion engines" (5-th semester) and "Marine Machinery Maintenance and Repair" (6-th semester) was performed. Assessment of knowledge was performed in the test form.

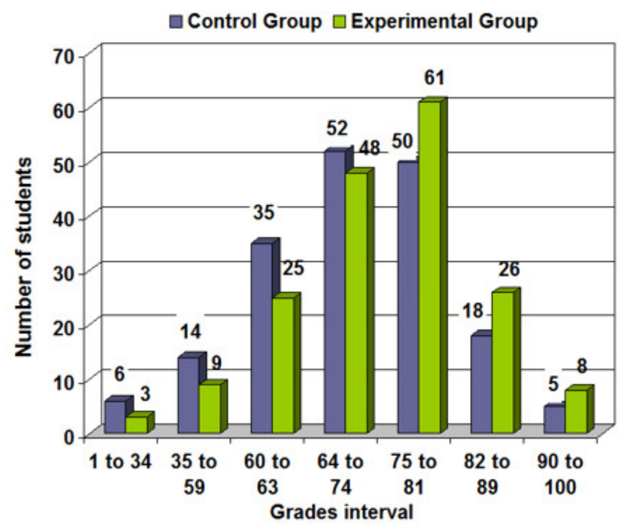
Figure 9: Students rating result (discipline "Marine Internal Combustion Engines", topic "Diesels movement parts design").



Source: Authors.

The results of knowledge assessment for the control and experimental groups are presented in the fig. 9 and fig.10. The results of the experiment made it possible to show that the applying of the proposed methodology and content of teaching the section "Redundant constraints in mechanisms" of the "Applied Mechanics" discipline allowed to intensify learning process of mentioned special disciplines and to enhance the achievement of special skills and competencies by future marine engineers.

Figure 10: Students rating result (discipline "Marine Machinery Maintenance and Repair", topic "Diesels movement parts maintenance and repair").



Source: Authors.

Conclusions.

Apparently, the main aspects that encourage students to study engineering are mainly motivational, as well as creating something new, or solving some complex operational problems. General engineering education is an important phase to show to the aspiring students that their main motives, being able to do and solve and to be technically challenged, are satisfied. At the same time, the learning of future marine engineers may be very specific, tied to the characteristics of the operational possession and specific powers to the first service, regulated by the IMO Model Courses. In this case, general engineering education sideways of specific skills achievement is not allowed to reach the maximum possible progress in the future specialty. In this article, an example of general and specific, required by courses 7.04 and 7.02, knowledge mutual integration in "Applied Mechanics" and specific academic disciplines, studying KSMA, is given.

Presented in this work case-study approach of "Redundant constraints in mechanisms" section learning tested over a number of years and gave the positive results. The following are specific conclusions that can be drawn from the observations made in the current work:

- case, extending "Applied Mechanics" academic discipline content for marine engineers, allowing to show the effect of redundant constraints on the design and common failures of marine diesel parts, which is often encountered in practice and understandable to students is developed;

- the developed case allows filling the vacuum existing in the special literature on "Applied Mechanics" for marine engineers. This makes it possible to facilitate the work of educators and students in the preparation and study of general engineering and specific disciplines;
- an experiment conducted over a number of years made it possible to establish that the application of the proposed approach to the study of the section "Redundant constraints in mechanisms" makes it possible to intensify the achievement of special skills and competencies of marine engineering specialties students. Particularly after the study of the topics "Diesels movement parts design" and "Diesels movement parts maintenance and repair" of, respectively, "Marine Internal Combustion Engines" and "Marine Machinery Maintenance and Repair" academic disciplines, the number of failed students decreased by 60%, learning quality increased by 25...30 % (the number of C, B, and A-graded students), the number of excellent students increased by 60...67%. This study further emphasizes the necessity to deepen teaching the "Applied Mechanics" course for future marine engineers, because its role is unmistakable in keeping up the specific education standards at a high level.

References.

1. Bulgakov, V.M. Applied Mechanics. Kyiv: CNL, 2020. 906 p.

2. Failure analysis case studies II. A sourcebook of case studies selected from the pages of Engineering. Failure Analysis 1997- 1999. Edited by D.R.H. Jones. Amsterdam; New York: Pergamon, 2001. 444 p.

3. Gero, A., Stav Y., Yamin, N. 2017. Use of real world examples in engineering education: the case of the course Electric Circuit Theory / World Journal of Engineering and Technologic Education, Vol. 15, No. 2, pp. 120 – 125.

4. Gulida, E.M. Applied Mechanics. Lviv: Svit, 2007. 384p.

5. Huang, C.-H. 2012. The role of examples in the learning of definite integral / World Journal of Engineering and Technologic Education, Vol. 10, No 4, pp. 236 – 240.

6. Matthews, C. Case Studies in Engineering Design. New York: John Wiley & Sons, 1998. 273 p.

7. Nastasenko V., Svyrydov V., Andreev A. 2022. New top-7 vessels wind projects and analysis of their practical possibilities for the transport fleet / Journal of Maritime Research. Vol. 19. No. 3. pp. 30 – 38. https://www.jmr.unican.es/index.php/-jmr/article/view/659.

8. Nastasenko V., Protsenko V., Babiy M. 2023. Modern development of ship wind systems within the new rating of Top-7 projects / Journal of Maritime Research. Vol. 20. No. 2. pp. 77 – 88. https://www.jmr.unican.es/index.php/jmr/article/view/716.

9. Osols, O.G. Theory of Mechanisms and Machines. Moscow: Nauka, 1984. 432p.

10. Pavlishche, V.T. Applied Mechanics. Lviv: Intelect-Zakhid, 2004. 368p.

11. Protsenko V., Babiy M., Nastasenko V., Protasov R. 2021. Marine diesel high pressure fuel pump driving failure analysis /Journal of Mechanical Engineering – Strojnícky časopis, Vol. 71, No. 2, pp. 213 – 220. https://doi.org/10.2478/scjme-2021-0031.

12. Protsenko V., Nastasenko V., Babiy M., Protasov R. Marine ram-type steering gears maintainability increasing / Journal of Mechanical Engineering – Strojnícky časopis. 2022; Vol. 72, ?2: 149-160. https://doi.org/10.2478/scjme-2022-0025.

13. Reshetov, L. Self-Aligning Mechanisms. Moscow: Mir Publishers, 1986. 528p.

14. Sabol, S., Case Studies in Mechanical Engineering: Decision Making, Thermodynamics, Fluid Mechanics and Heat Transfer. New York: John Wiley & Sons, 2016. 259p.

15. The medium-speed diesel engine with rotating pistons Z40. Tech. review. Sulzer Brothers limited. Switzerland, 1981. 14p.

16.https://www.substech.com/dokuwiki/doku.php?id=failures_of_engine_bearings_and_their_prevention.

17. Voinea, R., Atanasiu, M. 1959. Contributions a la Teorie geometrique des Vis / Buletinul Institutului Politichnic Bucuresti, No. 21, pp. 69 – 90.

18. Woodyard, D. Pounder's marine diesel engines and gas turbines. Oxford: Elsevier Butterworth-Heinemann, 2004. 914p.