Development of teaching materials for Cayley Hamilton matrix theorem on fixed pulley problem

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Article History
Received: 24 October 2025
Revised: 25 May 2026
Accepted: 22 July 2026

Keywords
Cayley-Hamilton Theorem
Fixed pulleys
Teaching materials

Abstract
The National Education System encourages the provision of teaching materials that support independent learning according to the Merdeka Curriculum. However, physics learning is still dominated by general textbooks that lack contextualization. Learning modules are an alternative, but most of them have not integrated advanced mathematical approaches systematically, especially in solving physics problems involving systems of linear equations. The Cayley-Hamilton theorem on matrices of order 2 and 3 is a relevant approach for fixed pulley dynamics material that is often considered difficult by students. The commonly used substitution-elimination method is considered less efficient, while the matrix approach offers a more systematic solution. Based on this, this study aims to develop teaching materials based on the Cayley-Hamilton theorem on matrices of order 2 and 3 in solving fixed pulley problems. The research method used is R&D. This study consisted of three stages, namely define, design, and develop through literature study and feasibility validation by expert assessors, user assessors, and students using a Likert scale. The validation results showed that the teaching materials obtained an average score of 4.50 with a percentage of 90.1% from expert assessors and 4.76 with a percentage of 95.16% from user assessors, resulting in an overall average of 92.63%, which is classified as highly feasible. In addition, the practicality test results showed an average score of 4.78 with a percentage of 95.60%, indicating that the developed learning module has a very high level of practicality. Thus, this teaching material is declared feasible and effective for use as teaching material in physics learning activities and has the potential to be tested as supporting material in preparing for the Olympics.

Wardhany, M, K, K., Supriadi, B., Meilina, I, L. (2026). Development of teaching materials for Cayley Hamilton matrix theorem on fixed pulley problem. *Momentum: Physics Education Journal*, *10*(1), 230-240. https://doi.org/10.21067/mpej.v10i1.12697

1. Introduction

The provision of appropriate teaching materials is an important component of physics learning because students need learning resources that support independent learning, conceptual understanding, and systematic problem solving (Razi., 2024). The implementation of this curriculum requires the availability of teaching materials that can support independent learning, competency achievement, and logical understanding of concepts (Asrizal et al., 2023). However, the use of teaching materials in schools is still dominated by textbooks that are general in nature and less relevant to the context of students' lives (Rasmi & Hendri., 2025). Therefore, physics teaching materials should not merely present formulas and exercises, but should also facilitate the connection between physical concepts, mathematical representations, and systematic problem-solving procedures.

One of the appropriate teaching materials to support independent learning is learning module. The development and implementation of physics learning modules need to consider the relationship between content analysis, students' learning needs, instructional design, and evaluation of the learning implementation (Boublil et al., 2024). A learning module can provide structured learning experiences that allow students to study concepts independently while following systematic explanations and problem-solving activities. The use of self-learning modules has also been associated with students' attitudes, study habits, and academic performance in science learning, indicating their potential to support independent learning (Mutya et al., 2023). However, the development of physics modules can be further strengthened by incorporating mathematical

doi: 10.21067/mpej.v10i1.12697
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ISSN: 2548-9135

representations and explicit problem-solving strategies, particularly when students are required to connect physical concepts with mathematical models.

Physics is a science that is closely related to everyday life and requires analytical and mathematical reasoning skills. Mathematical reasoning plays an important role in physics problem solving because students need to translate physical situations into mathematical representations and use these representations to construct and solve problems (Gifford & Finkelstein, 2021; Simamora et al., 2022). The ability to use multiple representations is also important in physics learning because students need to connect symbolic, mathematical, visual, and conceptual representations when understanding physical phenomena (Munfaridah et al., 2022). Students may experience difficulties when they have to integrate conceptual understanding with mathematical representations during physics problem solving (Gifford & Finkelstein, 2021; Munfaridah et al., 2022; Nurul, D., 2022). Therefore, a mathematical approach that integrates physics concepts systematically and meaningfully is needed to help students develop more effective problem-solving processes.

One relevant mathematical approach is the Cayley–Hamilton theorem, which relates a matrix to its characteristic polynomial and provides a mathematical basis for matrix operations and applications (Kobal, 2025; Almeida et al., 2024). It can support the study of matrix representations and abstract mathematical structures while offering an alternative approach to solving systems of equations in matrix form (Kobal, 2025). Its potential to connect advanced mathematical concepts with physics problem solving makes it relevant for systematic physics learning. However, teaching materials that explicitly integrate the Cayley–Hamilton theorem into physics problem solving remain limited. Previous applications include determining matrix inverses (Almeida et al., 2024), quantum matrix algebra (Ogievetsky & Pyatov, 2021), and two- to three-loop electrical circuits (Supriadi et al., 2024).

Motion dynamics material on a fixed pulley system is one of the physics topics that is considered difficult by students. The difficulty requires students to connect conceptual understanding with mathematical procedures, including identifying variables, constructing equations, and determining physical quantities (Jian, 2022; Gifford & Finkelstein, 2021). Students need to construct appropriate mathematical models before performing calculations, particularly when dealing with multiple interacting forces. Systematic explanations and structured solution steps can support students in developing effective physics problem-solving processes rather than relying solely on formula application (Gjerde et al., 2022). Therefore, the use of systematic mathematical representations is important in solving fixed pulley problems, especially when Newton's second law produces systems of linear equations involving multiple variables (Ilmi et al., 2023).

The System of Linear Equations (SPL) in the fixed pulley problem can be formulated in matrix form and solved using various methods such as substitution, Cramer's rule, inverse method, and Gauss-Jordan elimination method (Aida et al., 2023). However, the Cayley–Hamilton theorem offers an alternative matrix-based approach by relating a square matrix to its characteristic polynomial, providing a mathematical foundation for matrix operations and applications (Kobal, 2025; Almeida et al., 2024). The use of mathematical representations can support students in connecting abstract mathematical structures with scientific concepts and systematic problem-solving processes (Munfaridah et al., 2022; Prain et al., 2023). Therefore, integrating the Cayley–Hamilton theorem into physics learning has the potential to provide a systematic alternative for solving systems of linear equations arising from physics problems. However, teaching materials that explicitly integrate this theorem into physics problem solving remain limited.

Based on interviews with physics teachers at schools in Jember City, it was found that the elimination-substitution method is still predominantly used to solve pulley problems, including complex Olympic-level problems, making it difficult for students to construct logical and efficient systems of equations. The teaching materials used are also still limited to the Subject Teacher Working Group (MGMP) book, textbooks, syllabi, and modules that do not yet present innovative and systematic mathematical approaches. This condition shows that although effective in simple systems, the elimination-substitution method becomes less efficient in compound pulley systems, thus creating an urgency to use a matrix approach through the Cayley-Hamilton Theorem. Therefore, this study aims to validate the development of learning modules that integrate the Cayley–Hamilton

Theorem in 2nd and 3rd order matrices as innovative teaching materials to support more effective, systematic, and independent physics learning.

2. Method

The research method used is Research and Development (R&D) with the 4D development model (Define, Design, Develop, Disseminate) in research into three stages, namely define, design, and develop. The define stage includes analyzing learning needs. The design stage includes the development of teaching materials and the preparation of evaluation instruments. The develop stage includes product development and validation by six validators, consisting of three Physics Education lecturers at the University of Jember in the field of mathematical physics and learning media and three high school teachers in the field of physics (Figure 1).

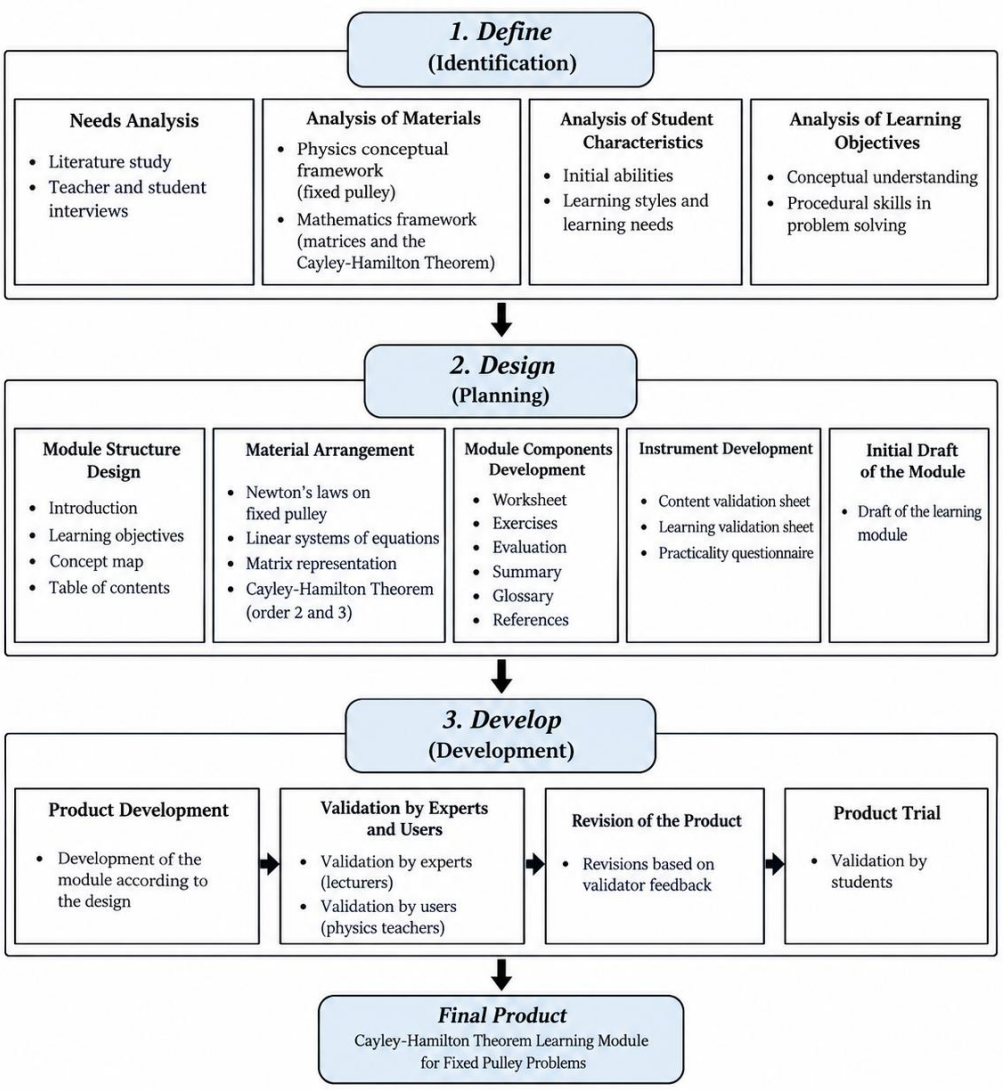


Figure 1. Stages of Module Development

Validation of teaching materials for the Cayley-Hamilton theorem of matrices of order 2 and 3 in solving fixed pulley problems. The focus of the research lies on the literature review and theoretical analysis of the utilization of matrices of order 2 and 3 in determining the acceleration and tension of the rope on a fixed pulley system. The results of the analysis are used as the basis for the preparation of teaching material development in the form of physics learning modules. The research was carried out at the Advanced Physics Laboratory, Physics Education Study Program, FKIP University of Jember, and in high schools in Jember City in the odd semester of the 2024/2025 academic year.

The validation instrument covers four aspects, namely content eligibility, material presentation, language, and graphics (Boublil et al., 2024; Mutya et al., 2023). Rated on a 1-5 Likert scale as in Table 1 below.

Table 1. Likert Scale Rating

Category	Score
Very Good	5
Good	4
Fairly Good	3
Poor	2
Very Poor	1

(Riski et al., 2025).

The data from the validation results were analyzed using the percentage formula in Equation (1), namely

$$P = \frac{k}{n} \times 100\% \quad (1)$$

The formula is to determine the level of feasibility. The validation results are then categorized into five levels as in Table 2 below.

Table 2. Feasibility Category

Interval (%)	Category
80< P ≤ 100%	Very Feasible
60%< P ≤ 80%	Feasible
40% <P ≤ 60%	Fairly Feasible
20%< P ≤ 40%	Inappropriate
P ≤ 20%	Very Inappropriate

(Riski et al., 2025).

Teaching material products are declared feasible to be tested in learning if they get a percentage value of more than 60%.

To complement the teaching material feasibility test, this study also applied a teaching material practicality test and an analysis of student errors at the development stage. The practicality test was conducted through limited trials with high school students who had studied fixed pulleys and matrices. The instrument used was a student practicality questionnaire with a 1-5 Likert scale covering three aspects, namely the benefits of the module, the presentation of the material, and the appearance and readability. The results of the teaching material practicality test were then classified into categories as shown in Table 3.

Table 3. Practicality Category

Interval (%)	Category
80< P ≤ 100%	Very Practical
60%< P ≤ 80%	Practical
40% <P ≤ 60%	Fairly Practical
20%< P ≤ 40%	Impractical
P ≤ 20%	Very Impractical

Teaching materials are considered practical if they obtain a practicality percentage of ≥ 80% and very practical if they obtain a percentage of ≥ 90%.

3. Results and Discussion

This research resulted in the development of Physics teaching materials based on the Cayley-Hamilton matrix theorem to solve fixed pulley problems. So far, solving the fixed pulley system generally uses the substitution and elimination method in solving a system of linear equations (SPL) based on the application of Newton's second law. Mathematically, there are alternative methods, such as the Cayley-Hamilton theorem, that can solve SPL of two or three variables analytically and

numerically with a more systematic approach. Although it has been proven effective, the application of this theorem is still rarely found in teaching materials and classroom learning practices.

The process of developing teaching materials based on the Cayley-Hamilton theorem on fixed pulley problems is carried out through three stages of 3D model development, namely define, design, and develop. Each stage has a specific role in ensuring the quality and usefulness of teaching materials. The following is a description of the results of each stage.

3.1. Define Stage

The define stage aims to identify learning needs and problems faced by teachers and students in understanding fixed pulley material. At this stage, researchers conducted interviews and literature reviews.

Direct interviews with high school physics teachers in Jember City, to obtain information about the methods commonly used in solving fixed pulley systems and the difficulties faced by students, especially in the mathematical aspect. The teacher said that the solution methods used are generally substitution and elimination methods in solving systems of linear equations (SPL). Students often experience difficulties, especially when the mass of the pulley is taken into account, because they do not understand the concept of moment of inertia and the relationship between Newton's law and mathematical equations. In addition, the teaching materials used are still conventional and have not integrated systematic mathematical methods such as the Cayley-Hamilton theorem.

A literature review, conducted to identify the potential use of the Cayley-Hamilton theorem in solving fixed pulley systems, showed that this theorem is worth using as an alternative approach in physics learning, especially in the context of matrix algebra. The output of the define stage is the formulation of the need for innovative teaching materials that integrate a mathematical approach based on the Cayley-Hamilton theorem to make it easier for students to understand the concept of fixed pulley dynamics.

Thus, the results of interviews and literature review show that students' understanding of pulley material remains low, especially if the mass of the pulley is taken into account. The use of elimination and substitution methods is not enough to help students connect physics and algebra concepts. In addition, the teaching materials used do not provide a systematic approach in solving SPL. Based on these findings, the preparation of a module based on the Cayley-Hamilton theorem is considered an innovative solution because it integrates physics and mathematics concepts logically and gradually.

3.2. Design Stage

At the design stage, the structure and content of teaching materials in the form of printed learning modules are compiled. The design of this teaching material refers to the structure of teaching materials according to Boublil et al (2024) which consists of an introduction that includes (1) background, learning outcomes, learning objectives, brief description of module content, concept map, benefits, and instructions for using the module; (2) presentation of subject matter, discussing fixed pulleys based on Newton's law and solving SPL using substitution and elimination methods (Chapter 2), as well as the application of the Cayley-Hamilton theorem in solving SPL for a fixed pulley system with pulley mass (Chapter 3); (3) sample problems and practice problems, each chapter is accompanied by contextual problems and exercises to strengthen students' understanding; (4) evaluation, including final evaluation questions with guidelines for assessing learning outcomes; (5) summary and enrichment, to clarify and deepen the material; and (6) glossary and bibliography, helping students understand important terms and showing the reference sources used. At this stage, visual design was also made, including cover, page layout, and selection of fonts, colors, and graphics to support readability and aesthetics.

The components contained in the teaching materials have been prepared based on the guidelines used in this study, which refer to (Boublil et al., 2024). The module structure is designed to support conceptual and procedural understanding. The material is arranged systematically, starting from Newton's law, SPL preparation, to the application of the theorem in solving second and third-order matrices. Examples of contextual problems and graphic visualizations support students'

understanding. The visual design and layout also pay attention to the grammatical aspects so that the teaching materials are attractive and easy to understand. This is in line with the findings of Hufri et al (2022) and Riski et al (2025), that the appearance of teaching materials affects student interest and understanding.

3.3. Develop Stage

The development stage is the stage of compiling complete learning modules based on the results of the design in the previous stage. At this stage, the compiled modules are then validated by experts and users to assess the suitability of the modules from various aspects, and tested on students to determine the practicality and usability of the modules in learning activities.

3.3.1. Validation by Expert Assessors

The validation was conducted by three Physics Education lecturers at the University of Jember. The assessment used a Likert scale instrument that covered four aspects, namely aspects of content eligibility, presentation, language, and graphics. The results are shown in Table 4.

Table 4. Results of Feasibility of Teaching Materials by Expert Appraisers

No.	Aspects	Score			Average	Percentage	Category
		V1	V2	V3			
1	Content	4.56	3.89	4.89	4.44	88.89 %	Very Feasible
2	Presentation	4.6	4	4.9	4.5	90 %	Very Feasible
3	Language	4.37	4.37	4.87	4.54	90.83 %	Very Feasible
4	Graphics	4.5	4.2	4.9	4.53	90.67 %	Very Feasible
Average		4.51	4.12	4.9	4.50	90.1 %	Very Feasible

The overall average score obtained was 4.50 with a percentage of 90.1% which was classified as very feasible. In addition, there are suggestions for improvement from expert assessors including simplifying the steps of applying the theorem, adding sample problems, thickening important words, increasing font size, and strengthening the justification for using the theorem.

3.3.2. Validation by User Assessors

User validation was conducted by three physics teachers teaching at senior high schools in Jember City, East Java Province. The assessment was conducted on the same aspects, and the results are shown in Table 5.

Table 5. Feasibility Results of Teaching Materials by User Assessors

No.	Aspects	Score			Average	Percentage	Category
		V1	V2	V3			
1	Content	4.78	4.44	5	4.74	94.81%	Very Feasible
2	Presentation	4.9	4.4	4.6	4.63	92.67%	Very Feasible
3	Language	4.87	4.75	4.75	4.79	95.83%	Very Feasible
4	Graphics	5	4.6	5	4.87	97.33%	Very Feasible
Average		4.88	4.55	4.83	4.76	95.16%	Very Feasible

The overall average score was 4.76 with a percentage of 95.16%, with a very feasible category. In addition, suggestions from users include the need for additional guidance on matrices for regular students because matrix and pulley materials are taught in different semesters. The module is very suitable for Olympic students or superior classes.

The results of the development stage show that the teaching materials developed have been tested for feasibility and declared very feasible to be applied in learning. The teaching materials in the form of learning modules have met the quality criteria from the aspects of content, language, presentation, and graphics. The content of the module is considered in accordance with the curriculum, conceptually complete, and accurate in the application of the Cayley-Hamilton theorem. The presentation is organized coherently, logically, and encourages active learning, while the use of language is easy to understand and by the rules of language. Graphically, the module design is considered consistent, attractive, and supports understanding. This finding is in line with the research of Riski et al (2025) and Aida et al (2023) which stated that numerical and visual approaches

in teaching materials effectively improve understanding. Research by Kobal (2025) and Almeida et al (2024) also confirmed the efficiency of using the Cayley-Hamilton theorem in solving linear systems. Other advantages of this teaching material include the use of a systematic and efficient mathematical approach compared to the substitution-elimination method (Almeida et al., 2024), attractive visualization (Riski et al., 2025), and clear symbol structure and language (Arifuddin et al., 2022). Besides being relevant for regular learning, this module can also be used in fostering outstanding students, such as physics olympiad guidance.

The validation results from experts and users show that teaching materials based on the Cayley-Hamilton theorem on matrices of order 2 and 3 in the context of fixed pulley problems have a very good level of validity and are very feasible to be tested in learning. The development of this learning module is motivated by the need for teaching materials that can overcome the difficulties of students in understanding the complex concept of fixed pulleys, including those related to the moment of inertia. This finding is reinforced by research by Aida et al (2023), which emphasizes the importance of a systematic approach in understanding mathematical concepts in physics, as well as the research of Riski et al (2025), which shows that innovative teaching materials can improve interest and learning outcomes. Other studies, such as Murni et al. (2024), also show that the validity of teaching materials, both digital and printed, contributes positively to learning effectiveness. By paying attention to learning outcomes, integration of mathematics and physics concepts, and the completeness of the material, this teaching material was developed as a learning solution. With excellent validation from experts and users, this teaching material is expected to be an effective learning alternative in understanding fixed pulley problems using the Cayley-Hamilton theorem on second and third-order matrices.

3.3.3. Practicality of Teaching Materials by Students

The teaching materials that were developed were then tested on a number of students with the aim of determining the practicality and usability of the modules in learning activities. The practicality assessment covered three main aspects, namely the usefulness of the modules, the presentation of the material, and the appearance and readability. The results of the practicality test of the teaching materials by students are presented in Table 6and visualized in Figure 2.

Table 6. Results of Teaching Material Practicality by Students

Assessment Aspects	Average score	Percentage (%)	Category
Module benefits aspects	4.84	96.80	Very practical
Material presentation aspects	4.70	94.00	Very practical
Appearance and readability aspects	4.80	96.00	Very practical
Total average	4.78	95.60	Very practical

Based on Table 6, the results of the teaching material practicality test show that the learning module is in the very practical category in all aspects of assessment. The module's usefulness aspect received an average score of 4.84 with a percentage of 96.80%, indicating that the module greatly helped students understand the material, supported independent learning, and facilitated the solution of physics problems related to the application of Cayley–Hamilton's theorem to fixed pulley problems. The material presentation aspect received an average score of 4.70 with a percentage of 94.00%, indicating that the material was presented systematically, coherently, and was easy to understand through the explanation of concepts, examples, and practice questions. Meanwhile, the appearance and readability aspect received an average score of 4.80 with a percentage of 96.00%, indicating that the visual design, layout, and mathematical language and notation in the module were considered clear and easy to use. Overall, the average total practicality score of 4.78 with a percentage of 95.60% confirms that the developed learning module has a very high level of practicality, making it suitable and effective for use as teaching material in learning activities.

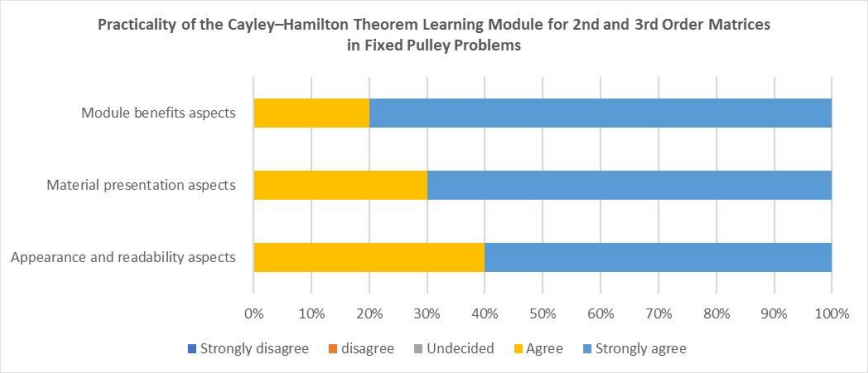
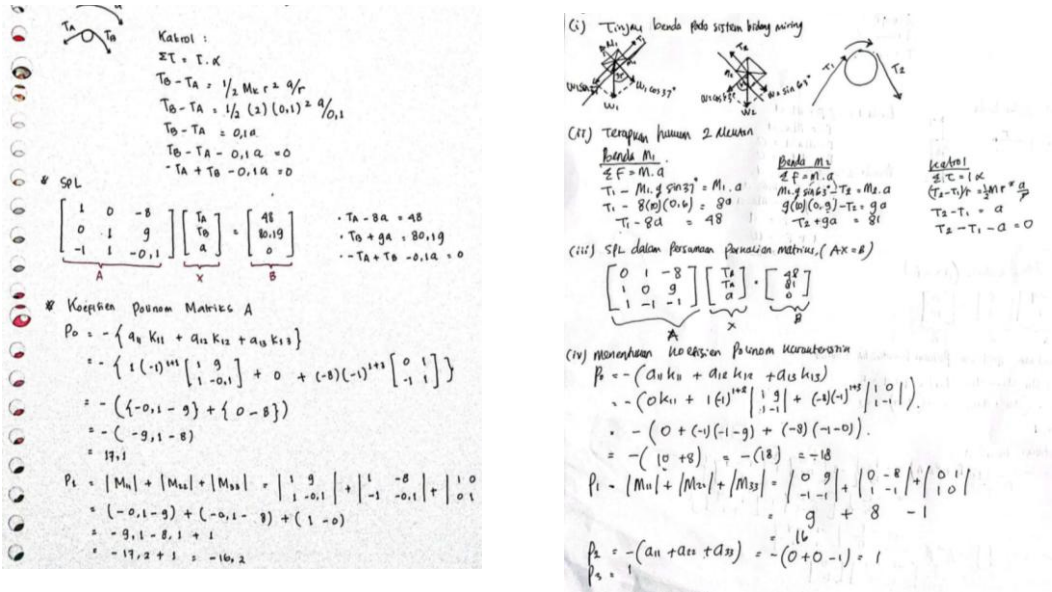


Figure 2. Diagram of the Practicality of Teaching Materials by Students

Figure 2 visually shows the level of practicality of teaching materials based on student assessments of each aspect tested. Based on the graph, it can be seen that 60% of students gave a rating in the strongly agree category (score of 5), while 40% of students gave a rating in the agree category (score of 4) for all aspects of the assessment. This indicates that there were no negative or neutral responses from students to the developed learning module. The aspects of module usefulness and appearance and readability had the highest percentages, indicating that students not only felt the benefits of the module in terms of content, but also felt comfortable using it. Meanwhile, although the material presentation aspect had a slightly lower percentage than the other aspects, it remained in the very practical category, indicating that the flow of material presentation was in line with the needs and characteristics of the students. Thus, Figure 2 reinforces the findings in Table 6 that the developed learning module has optimal usability in supporting the learning process.

The students' answers to questions on pulleys with 2nd and 3rd order matrices solved using Cayley–Hamilton's theorem were analyzed to determine the suitability of the steps taken by the students in accordance with the guidelines contained in the developed learning module. These difficulties were particularly evident in determining the coefficients of linear equations involving moment of inertia in the form of a third-order matrix, as shown in Figure 3.



(a) **(b)**

Figure 3. (a) Incorrect Answer for Determining Linear Equation Coefficients; (a) Correct Answer for Determining Linear Equation Coefficients

In the next stage, students who are less careful in their calculations tend to make numerical errors that continue until the final stage of completion. However, in terms of the flow and systematics of the solution, in general, students have followed the solution steps in accordance with the guidelines contained in the learning module, starting from physical modeling, matrix formation,

determination of characteristic polynomials, to matrix substitution based on Cayley–Hamilton's theorem. The errors that appeared were predominantly procedural in nature, namely a lack of accuracy in performing algebraic operations and numerical calculations, which resulted in inaccurate final results. This can be observed in Figure 4.

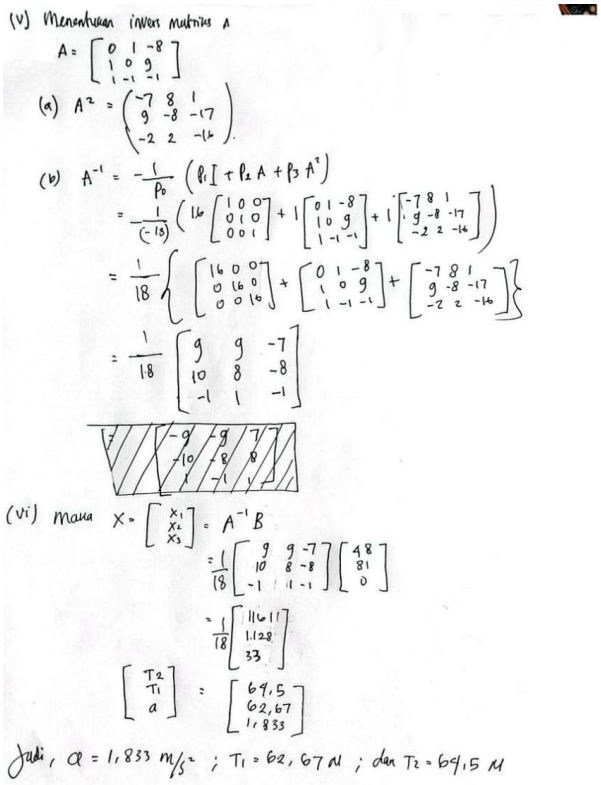


Figure 4. Numerical Errors that Continue until the Final Stage of Completion

These findings indicate that students who systematically follow the module guidelines, starting from physical modelling, matrix formation, determination of characteristic polynomials, to matrix substitution, tend to obtain the correct solution. Conversely, students who are less careful in their calculations, even though they have followed the correct solution flow, still experience numerical errors that affect the accuracy of the final result.

4. Conclusion

Based on the results of research and discussion, the teaching material design in the form of a learning module on Cayley–Hamilton's theorem for 2nd and 3rd order matrices in pulley problems has excellent quality in terms of content, presentation, language, and graphics. The validation results show an average score of 4.50 with a percentage of 90.1% from expert assessors and 4.76 with a percentage of 95.16% from user assessors, resulting in an overall average of 92.63%, which is classified as very feasible. In addition, the results of the practicality test in terms of benefits, presentation, appearance, and readability showed an average score of 4.78 with a percentage of 95.60%, indicating that the developed learning module has a very high level of practicality. Thus, this teaching material is declared feasible and effective for use in the physics learning process, both in regular classes and as supporting material for physics Olympiad preparation, and has the potential to be used as a reference in the development of innovative teaching materials and further research.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

Funding

No funding support was received.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability

The datasets generated during and/ or analysed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

Acknowledgement

The authors would like to thank all those who have contributed to the preparation of this article. This research can be carried out well thanks to the support and assistance of various parties. Special thanks go to the Supervisor who has provided guidance, direction, and input that is very meaningful during the process of preparing this article. The author also expresses appreciation to all those who have been pleased to review, review, and provide constructive suggestions for the development and improvement of the scientific quality of this article.

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