Evaluating ChatGPT's Engineering-Reasoning Capabilities and Constraints Through Examples from Mechanical-Engineering Education

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Abstract

This paper evaluates the mechanical engineering reasoning capabilities of ChatGPT-4, an advanced Large Language Model (LLM), with the aim of enhancing mechanical engineering education. Mechanical engineering education extends beyond text comprehension, a domain for which ChatGPT is renowned. It aims to nurture future engineers to become critical thinkers, who are proficient in applying acquired knowledge to execute complicated engineering tasks. However, there's an apparent gap in understanding how ChatGPT can be effectively integrated into educational practices within this specialized area due to a lack of detailed insights into its abilities and limitations. This research seeks to fill this void by exploring and assessing ChatGPT's reasoning abilities and limitations within the context of mechanical engineering. It examines the capabilities and constraints of ChatGPT in engineering reasoning by analyzing two mechanical examples, which are drawn from machine design and dynamics. By comparing ChatGPT's entire reasoning process and individual steps with human reasoning, this investigation unveils both its constraints and capacities. The results show that ChatGPT's limited capability to understand the profound implications of text. It addresses the need for caution when employing it in reasoning tasks within the context of mechanical engineering education.

Key words: mechanical engineering education, ChatGPT-4, engineering reasoning.

1. Introduction

Reasoning skill, often denoted as logical reasoning, constitutes the cognitive ability to engage in clear, structured thinking, analyze information, and logically derive valid conclusions on the foundation of evidence and facts [1]. Within the domain of mechanical engineering education, the

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cultivation of reasoning skills play an important role, representing a fundamental and pivotal objective in various engineering fields such as machine design, manufacturing, etc.

Engineering reasoning skills, such as the foundational process of concept derivation, are applied and required across mechanical engineering courses [2]. These skills highlight the extraction of profound insights from the mechanical engineering principles. Those demand not only an advanced mathematical ability but also a comprehension of their real-world implications.

Furthermore, the salience of reasoning skills becomes sound in the process of decision-making, particularly within the context of engineering design, which plays core place among engineering activities. Moreover, it stands as an essential step when engineers conduct optimization, design, and innovation [3]. The engineering reasoning skills are required to conceive, analyze and refine engineering solutions. However, confronted with optimization and design quandaries, students in the mechanical engineering major are challenged to harness reasoning and critical thinking in their learning processes for many reasons.

First of all, the solution to practical engineering questions is open-ended, yet the approach to reaching a solution should be rigorous in the reasoning process, which propose a high requirement to the engineers themselves. Secondly, students are new to the subject matter. When they are dealing with complex concepts, they often find it challenging to independently validate their reasoning without the guidance of instructors. Furthermore, the constraints of covered topics within finite time frames complicate the nurturing of reasoning abilities as well.

Nowadays, the utilization of AI tools, especially ChatGPT, has been observed being more popular as supportive aids in the learning process among engineering students. In light of this evolving educational landscape, it becomes imperative for educators to deepen the understanding of the capabilities and constraints of ChatGPT. Such an exploration to yield valuable insights, informing our strategies for wisely integrating AI into the engineering education.

2. Related Work

Studies have delved into the exploration and evaluation of ChatGPT's influence on engineering and its educational fields. *Matthew E. Frenkel* and *Hebah Emara* scrutinized ChatGPT's abilities in solving the mechanical engineering problems [4]. The study involved questions from junior and senior level mechanical engineering exams and the Fundamentals of Engineering Exam (FE) [5]. While GPT-4 and GPT-3.5 achieved 76% and 51% correctness, respectively, the research revealed limitations in ChatGPT's performance, suggesting a preference for expert guidance [6]. These findings offer valuable insights for educators in mechanical engineering, although the evaluation of ChatGPT's diverse capabilities remains a topic for further exploration.

Armero Martinez et al. focused on ChatGPT's utility in supporting engineering project development [7]. The study illustrated the potential of ChatGPT in aiding human tasks related to documentation, regulations, formula calculations, and equipment selection [8]. The results indicate the capacity to revolutionize engineering work, enabling the resolution of complex challenges [9].

In manufacturing fields, *Silvia Badini et al.* addressed the potential of Chat Generative Pre-trained Transformer (ChatGPT) in enhancing the efficiency of Gcode generation for Additive

Manufacturing (AM), along with its challenges [10]. The research showed ChatGPT's ability in tackling complex tasks, indicating its promise in time and cost savings for manufacturers and industries. *Xingzhi Wang et al.* assessed ChatGPT's potential contributions to the future of the industry [11]. This study employed systematic questions in the manufacturing field, demonstrating ChatGPT's proficiency in addressing fundamental knowledge and basic application queries [12]. However, its performance waned when tackling intricate tasks such as technical design and machining parameter settings [13]. The results indicate promise but emphasize the need for more research on integrating ChatGPT into education [14].

In other educational areas, *Luis M. Sanchez-Ruiz et al.,* explored ChatGPT's potential impact in engineering education, particularly in mathematics [15]. The paper investigated how AI tools can influence critical thinking, problem-solving, and group work skills among students [16]. Through student feedback, it was concluded that ChatGPT's utilization presents novel challenges for engineering education [17].

Lastly, *Giulia Polverini* and *Bor Gregorcic* enhanced comprehension of LLMs in physics education, offering valuable insights for engineering education, given the intrinsic connection between fundamental physics and engineering knowledge [18].

While these studies collectively contribute to the understanding of ChatGPT's role in engineering and its educational field, there exists a substantial research gap in comprehending the potential of integrating ChatGPT in the mechanical engineering education, which has its unique features encompassing knowledge acquisition, application, calculation, reasoning, etc [19],[20]. Consequently, this paper aims to bridge this gap by investigating and evaluating the reasoning capabilities and constraints of ChatGPT-4.0 within the context of mechanical engineering.

3. ChatGPT in Mechanical Engineering Learning

ChatGPT, developed by OpenAI, represents a sophisticated natural language model known for its ability to engage in interactive conversations and provide intelligent responses [21]. This innovative model operates within a chat-based interface, allowing users to input text-based queries and receive corresponding text-based responses.

In higher education, ChatGPT has emerged as a valuable tool for enhancing mechanical engineering education in multiple ways, providing support to both students and educators. One of its key strengths lies in its capacity to illustrate complex concepts, leveraging its extensive knowledge base. Mechanical engineering includes a multitude of interconnected concepts, making it challenging for students to navigate without proper guidance. It serves as a valuable resource for students seeking rapid access to definitions and explanations [22]. Furthermore, it extends beyond the confines of the classroom, offering insights into real-world applications and cutting-edge technologies. Therefore, the uses of ChatGPT benefits in fostering higher learning efficiency and intriguing students' interests.

However, the integration of ChatGPT in mechanical engineering education carries inherent risks, especially when users possess limited familiarity with the technology and lack appropriate guidance for its use like undergraduates. Mechanical engineering is a discipline that involves more than mere text-based comprehension; it necessitates skills such as reasoning, mathematical

calculations, and inference, among others [23]. These multifaceted processes demand competencies beyond those required for text-based comprehension alone. Consequently, the distinctive characteristics of mechanical engineering present challenges when employing ChatGPT, particularly when students are in the early stages of their learning journey, making it difficult to identify potential errors. Therefore, it is imperative to critically assess both the capabilities and limitations of ChatGPT within the context of mechanical engineering. This paper focuses on evaluating the model's engineering reasoning capabilities and presents two examples to gain insights and offer guidance on the utilization of ChatGPT in mechanical engineering.

4. Example Studies

In mechanical engineering education, many courses place a pronounced emphasis on the derivation of equations, a task that inherently demands a high degree of engineering reasoning prowess, such as fluid, solid mechanics, machine design, etc. Many fundamental concepts in this discipline are rooted in the principles represented within fundamental formulas and precise definitions. As a result, the acquisition of proficiency in the derivation process assumes to be important for engineering students [24]. The benefits of this proficiency are not only facilitating a deep comprehension of engineering concepts but also unveiling the inherent physical implications. This dual insight proves essential in equipping students with the knowledge and skills, which are required to solve real-world engineering challenges in their future careers.

To assess ChatGPT's capabilities in engineering reasoning, this paper undertakes an exploration of two foundational, yet crucial concept derivations drawn from courses in Machine Design and Dynamics: *stiffness* and *centripetal accelerations*. These selected studies progressively escalate in complexity, thereby affording us the opportunity to evaluate ChatGPT's reasoning capabilities. We conduct a comparative analysis of the responses generated by both humans and ChatGPT, evaluating correctness, relevance, and the alignment of ChatGPT's answers with human-generated solutions. Our examination is presented in an in-depth discussion of ChatGPT's engineering reasoning abilities and their attendant limitations. The findings denote an area of potential improvement, revealing ChatGPT's relative deficiency in mathematical reasoning.

4.1 Derive "*Stiffness*" in Machine Design

Question Background: *Stiffness* is a mechanical property that quantifies the resistance of a material of structure to deformation when subjected to an external force or load [25]. It is a measure of how much a material or structure resists applied forces.

Question: Derive the beam's *stiffness* k for a linear elastic material.

$$k = \frac{EA}{L} \qquad\qquad (1)$$

where E is Young's Modulus of the material, A is the cross-sectional area of the beam perpendicular to the applied force, L is the length of the beam between the points where it's supported.

Answers from human:

Step 1: Start with Hooke's Law for linear elastic material.
$$\sigma = E \cdot \varepsilon \qquad\qquad (2)$$

where σ is stress, ε is strain.
Step 2: From the definition of stress,
$$\sigma = \frac{F}{A} \qquad\qquad (3)$$

where F is external forces.
Step 3: From the definition of strain,
$$\varepsilon = \frac{\Delta L}{L} \qquad\qquad (4)$$

where ΔL is the change of length.
Step 4: Substitute equation (3) and (4) back into (2), we can get
$$\frac{F}{A} = E \cdot \frac{\Delta L}{L} \qquad\qquad (5)$$

$$k = \frac{F}{\Delta L} = \frac{EA}{L} \qquad\qquad (6)$$

Thus, based on the definition of stiffness, we can get from the equation (6), which matches the equation (1).

Answers from ChatGPT:

> **CU** **You**
>
> Can you derive the beam's stiffness k= EA/L for a linear elastic material in the context of mechanical engineering?

Here's how to derive the formula:

1. Start with Hooke's Law for a linear elastic material, which relates stress (σ) to strain (ε):

   $\sigma = E * \varepsilon$

   - σ: Stress (force per unit area)
   - E: Young's Modulus (material property)
   - ε: Strain (dimensionless)

2. For a beam in bending, the stress is related to the bending moment (M) and the distance from the neutral axis (y) through the formula:

   $\sigma = M * y / I$

   - M: Bending moment (force times distance)
   - y: Distance from the neutral axis to the point of interest
   - I: Area moment of inertia of the beam's cross-section

3. Combine Hooke's Law and the stress-strain relationship for bending:

   $E * \varepsilon = M * y / I$

4. Express strain (ε) in terms of the displacement (Δy) and original length (L) of the beam:

   $\varepsilon = \Delta y / L$

5. Substitute ε in the equation:

   $E * (\Delta y / L) = M * y / I$

6. Rearrange the equation to isolate the bending moment (M):

   $M = (E * I / L) * \Delta y$

7. Now, consider the relationship between bending moment (M) and the applied force (F):

   $M = F * L$

   - F: Applied force

8. Substitute this into the previous equation:

   $F * L = (E * I / L) * \Delta y$

9. Solve for the displacement (Δy):

   $\Delta y = (F * L^2) / (E * I)$

10. The displacement Δy represents how much the beam deflects under the applied load.
    Now, let's define stiffness (k) as the ratio of the applied force (F) to the displacement (Δy):

    $k = F / \Delta y$

11. Substitute the expression for Δy:

    $k = F / [(F * L^2) / (E * I)]$

12. Simplify by inverting the fraction in the denominator:

    $k = (E * I) / (F * L)$

Several noteworthy observations emerge from this example:

ChatGPT's Potential for Misrepresentation. It is evident that ChatGPT can produce incorrect solutions during the reasoning process. In this specific case, it presented $k = \frac{EI}{FL}$ at Step 12 instead of the desired derivation. Notably, it employed the assertion "have derived the formula" to advance its response. This behavior suggests that ChatGPT has the capability to generate responses that do not align with the underlying principles, which can pose risks for students in mechanical engineering education. Such deceptive responses can lead to confusion and hinder the learning process, especially for students lacking prior experience.

Limited Understanding of Engineering Fundamentals. Comparing ChatGPT's answers with those generated by humans, it is apparent that ChatGPT relied on five equations (Steps 1, 2, 4, 7, and 10) with an unsuccessful attempt. This disparity highlights ChatGPT's restricted ability to comprehend and apply engineering knowledge accurately within the context of mechanical engineering. Reasoning tasks in mechanical engineering differ from pure mathematics, as they involve domain-specific knowledge and practical applications. For instance, calculating stress varies based on specific scenarios, and ChatGPT demonstrated a lack of clarity regarding which method to employ. Additionally, it introduced irrelevant terms, such as M, further underscoring its difficulties in organizing following reasoning.

Limitations in Strict Reasoning. ChatGPT exhibited clear errors in its reasoning process, notably from Step 11 to Step 12. According to ChatGPT's own reasoning steps, the result should have been $k = \frac{EI}{L^2}$. However, it provided an incorrect answer $k = \frac{EI}{L}$, in an attempt to align more closely with the desired outcome $k = \frac{EA}{L}$, as expressed in equation (1). This tendency to make mistakes in favor of fulfilling the intended goal, rather than prioritizing correctness, which might be caused by the influence of the reward mechanism within ChatGPT's training model. This characteristic introduces a substantial degree of uncertainty into the answers provided by ChatGPT.

The results clearly indicate discrepancies in ChatGPT's responses, particularly when comparing the final derivation obtained at Step 12.

4.2 Derive "*Centripetal Acceleration*" in Dynamics

We have chosen to examine another fundamental yet crucial concept, *acceleration*, within the framework of undergraduate mechanical engineering dynamics courses. This selection serves as a rigorous test of ChatGPT's capabilities in reasoning, calculation, and comprehension within the specialized domain of mechanical engineering. This particular problem presents heightened complexity, as it requires not only proficiency in calculations and knowledge recall

but also demands a deeper understanding of the interplay between mathematical principles and their physical significance.

Question Background: In dynamics, when an object is undergoing rotational motion, accelerations play a crucial role in describing how the object's rotational speed or direction of rotation changes over time. There are two types of accelerations based on different directions, which are *centripetal acceleration* $\overrightarrow{\alpha_c}$, and *tangential acceleration* $\overrightarrow{\alpha_t}$. In this study, we desire to derive the formula of the centripetal acceleration $\overrightarrow{\alpha_c}$.

Question: How to derive the centripetal acceleration $\overrightarrow{\alpha_c}$ in Dynamics?

Answers from human:
We use the vector method.
Step 1: Assume the acceleration is $\vec{\alpha}$, the velocity is $\vec{v}$, the angular velocity is $\vec{\omega}$, the radius of the rotation motion is $\vec{r}$. Based on the definition, we have,
$$\vec{v} = \vec{\omega} \times \vec{r} \tag{7}$$

Step 2: Based on the definition of acceleration and velocity, it is known that
$$\vec{\alpha} = \frac{d\vec{v}}{dt} \tag{8}$$
Step 3: Substitute the equation (7) into the equation (8), we have,
$$\vec{\alpha} = \frac{d(\vec{\omega} \times \vec{r})}{dt} \tag{9}$$
$$= \frac{d\vec{\omega}}{dt} \times \vec{r} + \vec{\omega} \times \frac{d\vec{r}}{dt}$$

Step 4: Since the definition of the velocity
$$\vec{v} = \frac{d\vec{r}}{dt} \tag{10}$$
Step 5: Thus, the centripetal acceleration $\overrightarrow{\alpha_c}$ can be written in
$$\overrightarrow{\alpha_n} = \vec{\omega} \times \frac{d\vec{r}}{dt} = \vec{\omega} \times \vec{v} \tag{11}$$

Step 6: Substitute equation (7) in equation (11), we have
$$\overrightarrow{\alpha_n} = \vec{\omega} \times \vec{\omega} \times \vec{r} = \omega^2 r \cdot \overrightarrow{e_n} = \frac{v^2}{r} \cdot \overrightarrow{e_n} \tag{12}$$
where $\overrightarrow{e_n}$ is a unit vector in the direction perpendicular to the trajectory tangent line.

Answers from ChatGPT:

> **CU** **You**
> How to derive the centripetal acceleration?

1. The definition of speed is:

   $v = ds/dt$

   Here, "ds" represents an infinitesimal change in the position "s" as the object moves a small distance during a small time interval "dt."

2. In circular motion, the object travels a distance equal to the circumference of the circle in one full revolution ($2\pi r$). So, you can express "ds" as:

   $ds = 2\pi r$

3. Now, let's differentiate "s" with respect to time "t" to find the linear speed "v":

   $v = ds/dt = 2\pi r/dt$

4. To find acceleration, differentiate "v" with respect to "t":

   $a = dv/dt = d(2\pi r/dt)/dt$

5. Simplify:

   $a = d(2\pi r)/dt^2 = 2\pi r/dt^2$

6. Since the angular speed (angular velocity) "ω" is defined as the rate of change of the angle "θ" with respect to time "t," we have:

   $\omega = d\theta/dt$

   In uniform circular motion, ω is constant, and it's related to the linear speed "v" by:

   $v = r\omega$

   Rearrange to find ω:

   $\omega = v/r$

7. Now, differentiate ω with respect to time "t" to find angular acceleration "α":

   $\alpha = d\omega/dt = d(v/r)/dt = (1/r)d(v)/dt$

8. Recall that linear acceleration "a" is related to angular acceleration "α" by:

   $a = r\alpha$

9. Substitute the expression for α:

   $a = r(1/r)d(v)/dt = d(v)/dt$

10. Finally, use the equation for linear speed "v" (from step 3):

    $a = d(2\pi r/dt)/dt = 2\pi r/dt^2$

Insufficient Mathematical Proficiency: ChatGPT's mathematical capabilities fall short of meeting the demands of college-level engineering learning. College-level mathematics often involves advanced concepts such as derivatives, partial derivatives, and more. This problem highlights ChatGPT's inability to perform calculations and differentiate between scalars and vectors.

Limited Grasp of Mathematical Equations' Physical Significance. In the engineering, definitions are not solely derived from mathematical formulations but also heavily rely on their physical significance and implications. "The distinction between the concepts of 'speed'

and 'velocity' is such an example. While the former is characterized as a scalar quantity, the latter assumes the form of a vector, including both magnitude and direction. Thus, a profound comprehension of the physical implications associated with these definitions is crucial for correctness.

Regrettably, the example at hand reveals ChatGPT's susceptibility to confusion on this matter, which becomes evident as early as Step 4 $a = \frac{dv}{dt} = \frac{d\left(\frac{2\pi r}{dt}\right)}{dt}$. At this step, ChatGPT mistakenly represent velocity in an arbitrary dynamic motion using a circular equation. This misconception subsequently leads to a sequence of wrong steps.

In contrast, the correct understanding, as demonstrated in Equation (7) within the human-provided answer, recognizes velocity as a vector entity, inclusive of both scalar magnitude and directional attributes. Such evidence holds significant weight when considering upon the derivation of engineering concepts.

Limited Capacity for Coherent Reasoning. While ChatGPT excels in retrieving relevant information from its database, as demonstrated from Step 1 to Step 6, it encounters challenges in integrating and applying this information cohesively for a specific task. This limitation is evident in Steps 8 and 9 of ChatGPT's solution, which redundantly recapitulate prior results, ultimately culminating in Step 10's provision of a wholly incorrect conclusion—a mere repetition of information from Step 5 $a = \frac{d\left(\frac{2\pi r}{dt}\right)}{dt}$.

It is evident that ChatGPT failed to resolve this problem, yielding a result that appears far-fetched, with a_c incorrectly equated to $\frac{2\pi r}{dt^2}$. The analysis of ChatGPT's solution reveals several recurring errors that highlight the limitations of its computational and reasoning abilities.

5. Conclusion

This paper delves into an exploration of the capabilities and constraints associated with the integration of ChatGPT into mechanical engineering education, with a specific focus on its reasoning abilities—an essential skill in engineering studies for fostering future engineers. Engineering reasoning demands a multifaceted skillset, encompassing knowledge acquisition, knowledge application, cognitive processes, analytical thinking, and decision-making, among others [26]. In light of the evolving landscape of AI tools and their increasing adoption by students, a deeper comprehension of their impact becomes imperative, both for learners and educators.

In this study, we leverage two fundamental questions from the domains of Machine Design and Dynamics to assess ChatGPT's proficiency in rigorous engineering reasoning. Human-generated solutions serve as benchmarks for evaluating ChatGPT's performance. The findings illuminate significant challenges in ChatGPT's ability to engage in reasoning tasks, including the risks of misrepresentation, a limited grasp of textual understanding and implications, and restricted proficiency in advanced mathematics. These limitations collectively contribute to suboptimal performance in reasoning-based assignments.

These results provide valuable insights for the field of engineering education, particularly for students in the early stages of their learning journey with limited practical experience. In conclusion, our study underlines the need for a cautious and conservative approach to the incorporation of ChatGPT in engineering education, particularly in tasks that are relevant on reasoning, with human educators continuing to play an irreplaceable role. To help faculties teaching similar subjects, we recommend the following strategies:

Discuss AI's Limitations and Ethical Issues. It's vital to teach students about AI's shortcomings, such as biases, inaccuracies, and mistakes. This can lead to a more comprehensive understanding of what AI can and cannot do.

Host Workshops on ChatGPT and Other AI Tools. Offer workshops or seminars that give students practical experience with AI technologies, showing how they can be used in engineering problem-solving. These sessions can include case studies where AI tools have been beneficial and detrimental and discussions on integrating such technologies into the learning process effectively.

Emphasize the Value of Learning from Mistakes. Students are likely to make errors, just as AI does. Teaching them to think critically and distinguish between correct and incorrect solutions, regardless of whether they're provided by AI or found in textbooks, is crucial.

Implement Periodical Feedback Activities. Set up ways for students to report back on their use of AI tools like ChatGPT. This feedback can inform curriculum adjustments and teaching strategies, ensuring they align with student needs and industry demands.

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