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The Design of High Stress-to-Mass Ratio Components and Mechanical Systems

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Introduction

The design of high stress-to-mass ratio components and mechanical systems is a crucial challenge across various engineering fields, particularly in aerospace, automotive, and high-performance machinery. The concept of stress-to-mass ratio essentially refers to the ability of a material or system to withstand mechanical stress (forces per unit area) while keeping its overall mass as low as possible. High-performance applications, such as spacecraft, high-speed vehicles, and specialized tools, demand components that can endure extreme forces without adding excessive weight. This demand pushes the boundaries of material science, manufacturing techniques, and design principles. In this paper, we explore the critical aspects of designing such components and systems, focusing on material selection, structural design, optimization methods, and real-world applications. Moreover, multidisciplinary plays a fundamental role in enhancing performance by reducing the mass and inertia of machine components. It is important for the future that the innovation process involves expertise from multiple disciplines.

Understanding Stress-to-Mass Ratio

The stress-to-mass ratio is a measure of how much load a component can bear relative to its weight. Components with high stress-to-mass ratios are particularly valuable in fields where weight is a significant constraint, such as aerospace engineering, where the need for lightness and strength is paramount. The ratio combines two key performance indicators:

Stress (σ)

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Doi:

The force per unit area within materials that arises from externally applied forces, uneven heating, or permanent deformation. The stress state in a machine element can be simple or complex. Structural mechanics and finite element modeling (FEM) help to determine complex stress states for components with complex geometries and notches.

Mass (m)

The mass of the component or structure, which contributes to its weight and inertia. The density of the material plays a fundamental role both for components that operate under static load application conditions and especially in load conditions where inertia plays a fundamental role. As an example, a gear in a reduction gear is reported, which, beyond the weight, shows an increase in the readiness and power of the machine. A high stress-to-mass ratio implies that a component can withstand high forces without significantly increasing its weight, making it an ideal candidate for applications requiring both strength and lightness. We are considering the state of stress and we are focusing on the verification of strength. Let's not forget that to reduce mass, the elastic modulus of the material is often reduced, for example by using lightweight alloys. In addition to designing for strength, it is also advisable to incorporate deformation design to avoid excessive displacements and deformations.

Material Selection for High Stress-to-Mass Ratios

One of the most critical decisions in designing such components is the selection of the appropriate material. The ideal material must possess both high strength and low density to maximize the stress-to-mass ratio. Several materials are commonly used in the design of high-performance systems, each with its unique advantages and limitations.

Titanium Alloys

Titanium is a favored material in aerospace and high-performance applications due to its impressive strength-to-weight ratio. Titanium alloys exhibit high tensile strength and good fatigue resistance, making them suitable for use in environments subjected to cyclic loading, such as jet engines and structural components of aircraft. Although titanium is more expensive than other metals, its performance justifies the cost for critical components.

Aluminum Alloys

Aluminum is lighter than titanium and is widely used in systems where weight is the most critical factor. While aluminum alloys have lower strength than titanium, their stress-to-mass ratio remains high, especially in applications like aircraft fuselages and structural components of rockets. The main challenge with aluminum alloys is their lower fatigue resistance compared to titanium.

Composite Materials

Advanced composites, such as carbon fiber-reinforced polymers (CFRPs), are often the material of choice for high-stress, low-mass applications. Carbon fiber composites offer exceptional strength and stiffness while being much lighter than metals. These materials have revolutionized industries like aerospace, automotive, and sports equipment manufacturing. Their major drawback is the high cost and challenges associated with their manufacturing processes, as well as their brittle nature compared to metals.

Carbon Nanotubes and Graphene

On the cutting edge of material science, carbon nanotubes (CNTs) and graphene offer extraordinary mechanical properties. CNTs, for instance, possess tensile strengths that exceed those of traditional metals by several orders of magnitude, while being lightweight. Graphene, known for its outstanding electrical and thermal properties, also holds promise for developing ultra-light and strong components. However, these materials are still in the early stages of research and commercialization, limiting their widespread application. Despite the lightness and low density of lightweight alloys, that make them very appealing, these are not suitable for applications where there are contacts between the elements of machines. In such cases, it is

advisable to study measures to mitigate the problems that could arise.

Design Strategies for High Stress-to-Mass Components

Once the material is selected, the next step is to design the component to maximize its stress-to-mass ratio. This involves considering the geometry, structural integrity, and manufacturing methods that will minimize mass without compromising strength.

Topology Optimization

Topology optimization is a computational design technique that helps in finding the best distribution of material within a given design space. By applying this method, engineers can create structures that are more efficient in terms of material use while maintaining or improving the strength-to-weight ratio. This technique is especially useful for complex geometries in aerospace and automotive components, where traditional design approaches might fail to achieve the optimal balance.

Structural Analysis and Load Distribution

When designing components that must withstand high stress, engineers perform extensive structural analysis to identify areas of maximum stress. Using tools such as Finite Element Analysis (FEA) [1-4], engineers can simulate how a component will behave under various loading conditions. This helps in determining the most efficient geometry and material distribution to handle stress without adding unnecessary mass.

Advanced Manufacturing Techniques

The design of high stress-to-mass ratio components often requires advanced manufacturing methods to ensure that the final product matches the design specifications. Additive manufacturing (3D printing), for example, allows for the creation of highly complex structures that are difficult to achieve with traditional manufacturing techniques. This technology enables the production of lightweight, optimized components with intricate geometries that are both strong and minimal in weight. Metal 3D printing, for example, can produce titanium or aluminum parts with customized porosity, which contributes to reducing the mass while maintaining strength.

Minimizing Fatigue and Failure

High-stress components are often subjected to repetitive loading, which can lead to fatigue failure. In the design process, it is crucial to account for fatigue strength, especially in components exposed to cyclic stresses, such as turbine blades or automotive suspension components. Design strategies such as incorporating fillet radii, reducing sharp corners, and optimizing material properties for fatigue resistance are important for ensuring durability.

Real-World Applications

The design of high stress-to-mass ratio components has transformative implications for various industries. The following examples highlight how these principles are applied in practice.

- Aerospace Industry
- Automotive and sustainable mobility application
- Healthcare and medical applications

In the aerospace sector, weight reduction is directly correlated with fuel efficiency and performance. Components such as engine parts, wings, and fuselages need to be both strong and lightweight. For instance, the use of composite materials in modern aircraft like the Boeing 787 has resulted in a significant reduction in weight, leading to improved fuel efficiency. Light alloys (aluminum, magnesium, titanium) and carbon fiber composites are widely used in the medical and automotive sectors due to their high strength-to-weight ratio. In automotive applications, they improve performance, energy efficiency, and safety by enabling lightweight yet strong structures. In the medical field, titanium and carbon are used for prosthetics,

orthopedic implants, and surgical tools thanks to their biocompatibility, corrosion resistance, and low weight, which reduces patient fatigue. In both industries, these materials enable innovative, durable, and sustainable solutions, offering advantages in performance, comfort, and longevity.

Conclusions

Designing components and systems with a high stress-to-mass ratio is a high-value engineering endeavor that combines materials science, structural mechanics, and computational tools. Success relies on a deep understanding of the interaction between stress, shape, and material, supported by modern optimization techniques and manufacturing technologies.

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