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A review on self-adaptive design elements

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Abstract

Adaptive systems in engineering adjust their properties in response to changing conditions such as load, temperature, or speed. Many existing implementations achieve adaptability through mechatronic systems incorporating actuators, sensors, and control systems, which often result in increased complexity, weight, and reduced robustness.

To overcome these drawbacks, systems are increasingly explored that achieve adaptability solely through their structural design and material behavior. In this work, the term 'self-adaptive' is used for these systems to highlight that adaptation emerges inherently from the properties of the structural elements themselves, without any external control. This leads to simpler, lighter, and more robust solutions.

This review focuses on the principles and applications of self-adaptive design and machine elements, such as bearings, seals, couplings, springs, dampers, housings, gears and shafts. A classification of design elements will be presented, along with an explanation of self-adaptivity principles. Additionally, an overview of the state of the art for specific design elements will be provided, followed by current and future research directions.

1 Introduction

Adaptive systems provide the ability to adjust their properties and behavior in response to changing environmental conditions or requirements. This includes, for example, the adjustment of shape, damping, and stiffness to maximize the efficiency and functionality of the system. Adaptive systems generally consist of a mechanical base system that includes load-bearing, spring, and/or motion elements. These elements ensure structural integrity while also providing the necessary degrees of freedom for adaptability. Adaptive systems are often implemented as mechatronic systems, where the mechanical base system is supplemented by actuators, sensors, and a control system. Actuators are used to apply targeted movements or forces, while sensors capture relevant environmental or system parameters and relay them to the control system, which in turn manages the energy flow to the actuators. However, such systems are often com-

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plex, which can lead to increased weight as well as reduced robustness, reliability, and availability, and can raise challenges related to sustainability and cost.

To overcome these disadvantages, current research and development approaches focus on the integration and merging of the fundamental components of mechatronic systems. So-called "smart structures" [1] are a prominent example of this. In these structures, the materials not only serve load-bearing functions but also possess actuation capabilities to, for instance, achieve adjustment movements. While such approaches can partially mitigate the aforementioned drawbacks, electronic components and control systems remain necessary, so that limitations related to complexity, robustness, reliability, and long-term sustainability persist.

For these reasons, research is partially pursuing a return to simpler, less complex systems by employing purely passive systems. These systems forgo the integration of separate mechatronic components such as actuators and sensors and instead rely on intelligent design principles and material applications, where adaptive capabilities are directly implemented at the structural level. Adaptation, in this case, is exclusively induced by changing operational loads, such as variations in load, temperature, and speed. In this review, the term *self-adaptive* is used to describe such passive systems, in which adaptability arises intrinsically from the mechanical or physical characteristics of the structural element. Although passive adaptive is a term found in parts of the literature, self-adaptive is adopted here to emphasize that no separate control logic or mechatronic integration is needed—the adaptability is an inherent feature of the component itself.

Self-adaptive systems represent an emerging field with significant potential to enhance the efficiency and functionality of engineering systems. By reducing system complexity while maintaining adaptability, such systems directly address key limitations of mechatronic approaches. Given their transformative potential, it is imperative to systematically determine the state of the art in technology and science to guide research and practical applications in this field. Additionally, identifying the key challenges and limitations in implementing self-adaptive systems will help to pave the way for their broader adoption and development.

In this review, we will focus on self-adaptive design and machine elements [2–5]. These elements are typically standardized in form and material to ensure their interchangeability and compatibility across various designs or machines. Examples include different types of bearings, seals, couplings, springs, dampers, housings, gears and shafts.

This paper is organized as follows: Section 2 introduces the terminology and classification of design elements (which encompass machine elements as a broader category). It defines the key terms used throughout the paper, distinguishes between different classes of adaptive systems, and highlights the specific properties and advantages of self-adaptive design elements. Section 3 discusses the principles by which self-adaptivity can be achieved across different scales—ranging from micro to macro level. These principles are grouped into five categories: materials, composites, metamaterials, elastic and kinematic. Each principle is illustrated with examples, including modeling approaches as well as their advantages and limitations. Section 4 surveys self-adaptive solutions in various design elements, including journal bearings, rolling bearings, gas foil bearings, seals, couplings, springs, dampers, housings, shafts, and gears. Each design element is examined with regard to current applications, untapped potential, and remaining research challenges. Section 5 summarizes the key insights from the application survey and presents them in a comparative overview table. Section 6 concludes the paper by discussing open challenges and promising directions for future research.

2 Classification, terminology and properties of adaptive machine and design elements

A design element is a fundamental building block in the development of machines or systems. The focus of this review is on mechanical design elements. A mechanical design element is a standardized component or part that is used in various technical systems to perform specific functions, such as carrying loads, enabling movements, connecting components or transmitting forces. Design elements from other domains such as electrical, electronic, or software are not considered. Although a distinction is sometimes made in the literature between design and machine elements [3], in this paper we subsume both under the general term design elements.

Design elements can be divided into two main categories: fixed and adaptive design elements. Figure 1 illustrates the detailed subcategories within each main category, using a truss element and a journal bearing as representative examples.

Conventional design elements are well-researched and have been employed for decades. These elements are typically purely mechanical [6] and are characterized by properties that remain constant during operation (apart from load- or temperature-induced elastic deformations that are usually regarded as unwanted interferences). As they are designed for specific operating conditions, deviations from these conditions can lead to suboptimal performance, such as increased friction or reduced strength. In this paper, we refer to such elements as fixed design elements to emphasize their unchanging properties during operation.

In recent years, the expansion of the functional range of conventional design elements has increasingly aroused the

interest of researchers [6, 7]. A subcategory of the fixed design elements are the so-called sensing design elements, which have been intensively researched in recent years [8]. Sensing design elements integrate in-situ sensor systems for data acquisition and processing for various process-relevant measurement tasks into conventional design elements. For example, information such as vibrations and local temperatures can be recorded, providing insights into the current operating state. A detailed classification of these elements can be found in Ref. [4], and a comprehensive overview can be found in the review by KIRCHNER ET AL. [8].

Adaptive design elements, as the second main category, are characterized by their ability to adjust their properties or behavior to suit different operating conditions [1, 9]. Importantly, this adaptation should not compromise their primary function. However, the terminology surrounding adaptive components is often inconsistent and ambiguous, making it difficult to establish a clear understanding of their design principles and functionalities. Terms such as adaptive, smart, intelligent, mechatronic, or adaptronic frequently appear in literature, but their usage is rarely precise or consistent [10–13].

This lack of clarity poses a challenge for research and development, as a shared understanding of these terms is crucial for classifying and advancing the field. To address this issue, it is important to delineate the differences between these terms and highlight their specific meanings.

In 1996, SPILLMAN ET. AL. [12] provided a foundational differentiation that remains relevant today:

- Adaptive: Refers to a physical adjustment to changes in the environment. For instance, an adaptive design element may change its stiffness or shape in response to external forces or temperature changes.
- Smart structures: Go a step further by optimizing their behavior for the current environmental conditions. However, in rapidly changing environments, smart structures often adapt based on slightly outdated conditions, as they rely on past data to make adjustments.
- Intelligent systems: Unlike smart structures, intelligent systems use past data to predict future conditions. They adapt proactively, not only to the current environment but also to anticipated changes. This distinction lies in the level of control sophistication.

In addition, the term adaptronics was introduced in 1991 by a working group of the Association of German Engineers (VDI) to describe systems in which all components of a conventional control loop (sensor, controller, actuator) are present and at least one of these components is multifunctional [10]. For example, a single component may serve as both a sensor and an actuator. JANOCHA [10] equated adaptronics with international terms such as smart materials, smart structures, and intelligent systems. However, as explained above, the terms “intelligent” and “smart” are

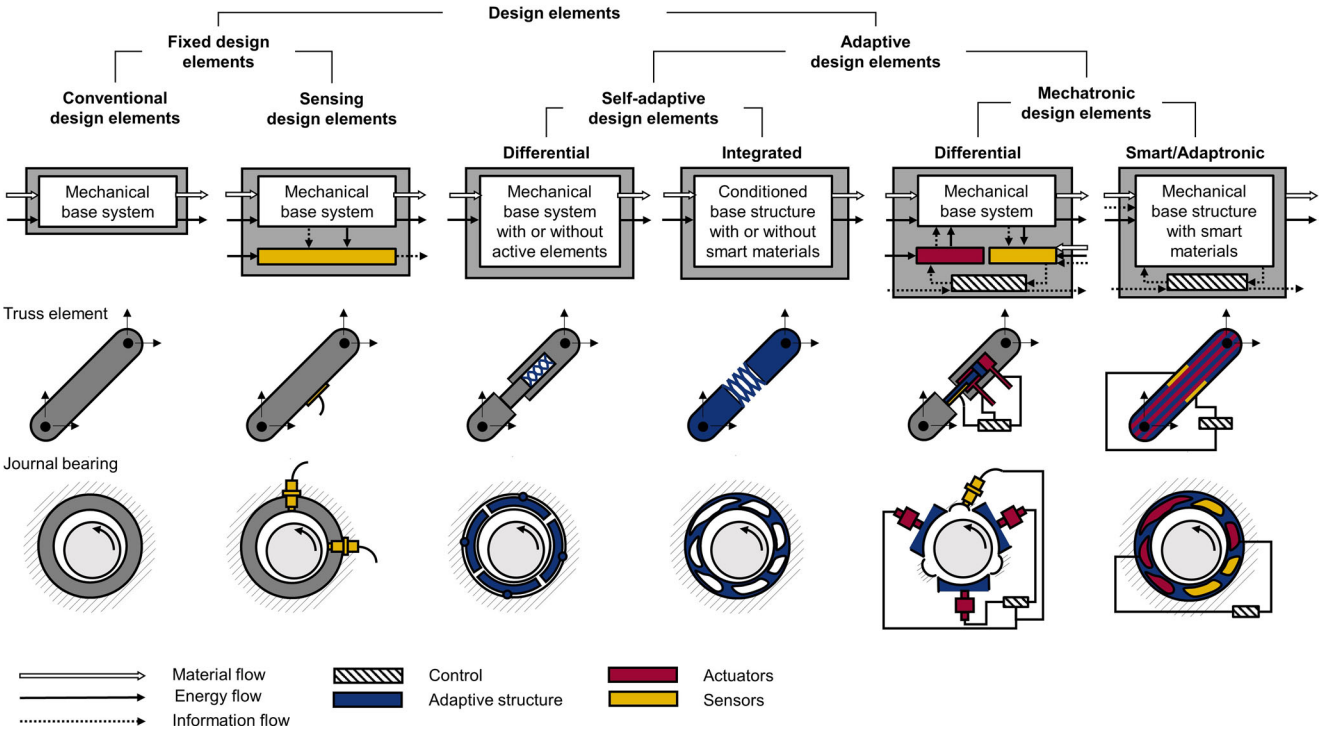


Fig. 1 Classification of design elements into fixed and adaptive design elements, each with schematic structure and two application examples (truss element and journal bearing)

not fully interchangeable. Additionally, the terms material and structure differ in their scale: materials describe properties at a microscopic level, while structures refer to the macroscopic arrangement of these materials. Therefore, the authors argue that the terms "smart" and "adaptronic" structures refer to the same type of systems, namely systems containing multifunctional components capable of performing sensory and actuation tasks, and which may include a control system [14]. However, the literature often remains unclear as to whether a control system is essential for these structures [10, 11].

Due to these terminological inconsistencies, this review adopts a clear classification to provide structure and precision: Adaptive design elements are divided into two subcategories:

- Self-adaptive design elements: These passively adjust their behavior based on the properties of their materials or structures in response to external loads, temperature, or speed change. This means that no electronics or information processing is integrated into the design elements [15] and no explicit actuation system is present.
- Mechatronic design elements: These actively adapt to environmental changes using integrated sensors, actuators, and control systems, which may be partially or fully integrated into the design elements and typically involve electronics and software for active regulation.

While the term mechatronic is widely used, the term self-adaptive is less common in the specific context defined here, though it appears sporadically [16–18]. So far, it has primarily been used from a computational point of view [19]. Since no standardized terminology exists for self-adaptive systems, relevant sources can be found under a variety of different terms, like passive [20] or passive adaptive [21]. By clarifying the terminology, this review aims to reduce ambiguity and provide a solid foundation for discussing adaptive systems and their role in advancing engineering design.

Self-adaptive design elements must meet the minimum criterion that they autonomously adjust at least one functional property in response to an external influence, such as force, pressure, or temperature—without relying on external control or energy input. This adjustment must emerge directly from the interaction of structural and material properties with the operating environment. Importantly, a clear distinction is made from mechatronic systems, which require external actuation sensors and information processing. While the definition of self-adaptive design elements given here includes simple classical components such as springs or seals, whose responses are passive and mechanically intrinsic—it also encompasses more sophisticated structures with smart materials, compliant structures, or complex geometries designed to respond differently under varying conditions. We intentionally adopt a broad interpretation of self-adaptivity, as even these simple classical components illustrate the underlying principle: adaptation that is inherent to the component's physical configuration and does not depend on discrete control logic or electromechanical subsystems. The term self-adaptive is therefore used to highlight that the adaptivity arises from within the element itself—by design—while the term passive adaptive is acknowledged as synonymous within the scope of this review.

Self-adaptive design elements can be categorized into differential and integrated self-adaptive design elements:

- Differential self-adaptive design elements: These rely on a modular mechanical system that is not optimized for a single operating state but can adapt to a range of operating conditions. This adaptability is achieved by incorporating mechanical subcomponents, such as springs or bearings, that adjust dynamically to external loads or conditions. The system's adaptability arises from the interplay of its individual components rather than from intrinsic material properties.
- Integrated self-adaptive design elements: These are based on a single structure or material system that inherently accommodates changing operating conditions. They often utilize smart or advanced materials and structures, such as shape memory alloys, piezoelectric materials and compliant mechanisms, which respond directly to environmental changes. Integrated elements typically have fewer components than differential ones, leading to simpler and more compact designs.

The second subcategory of adaptive design elements, mechatronic design elements, are created through the integration of mechanical and electronic components and processes with information technology. The aim is to find an optimal solution between the mechanical structure, sensor and actuator implementation, automatic digital information processing and control [6]. A typical mechatronic system detects changes in its environment through sensors, reacts to them after suitable information processing and converts control signals, for example, into forces and movements [22]. The external control of mechatronic design elements can be semi-active and active. Active methods interact with the system through controlled actuators that act directly on the degrees of freedom of the system [15]. Semi-active methods involve controlled actuators that act on the parameters of the system (such as stiffness) [23]. Both types of control require external energy, although the semi-active methods are more energy efficient [24].

In case of differential mechatronic design elements, the structure, sensor, actuator, and control are implemented as separate components. In contrast, adaptronic or smart design elements are characterized by a higher degree of func-

tional integration [11]. These systems incorporate multifunctional components that fulfill actuator and sensor functions and include a control system [14, 25], with actuators and sensors directly integrated into the structure. Achieving this level of integration requires the use of functional materials that enable actuator and sensory capabilities [10, 14].

A review of existing literature shows that there are major efforts to develop mechatronic design elements and that electronic components and processes with information technology are becoming increasingly important in contrast to the mechanical part (see for example [6, 22]). The great advantage of these design elements is that the presence of a controller enables more effective customization [26]. The use of digital real-time controls allows automatic adaptation to a wide range of environmental conditions [11] and enables a fast response time [27]. However, this comes at the cost of complexity, power consumption and potential stability issues [28]. The integration of components is constantly being driven forward in order to build the components as simply as possible, with the ultimate goal of reducing material and energy resources required for the implementation and operation to an absolute minimum [10].

This drive for efficiency aligns closely with the growing need to address societal challenges with regard to global warming, which cause specific challenges for engineers and the development of products. Sustainability in all its dimensions on a range from social sustainability along the entire supply chain, the need for products that are to be maintained and repaired easily, as far as legislative requirements for the application of re-usable and recyclable materials and components produce numerous and interconnected requirements to be considered. Additionally, competition on global markets leads to increasingly complex product requirements at reduced costs and timeline. These requirements are on the one hand driven by new product functions and on the other hand by the expectation of customers to purchase cost effective and long lasting products adapted to their specific needs. Therefore, products with a low number of components and little complexity support achieving actual requirements with regard to a wide range of competing objectives. With increasing number of parts and their increasing complexity in modern products, more material is used, which leads to higher weight and energy consumption, maintenance and repair require more effort with regard to time and tools, and recycling becomes complicated. Reliability and availability decrease due to an increased number of potential failures related to the number of parts and complexity of the technical system. Moreover, even the cooperation of stakeholders from different domains takes more time and causes more potential interface problems. Therefore, products that adjust their behavior—inherently by design, without the need of additional components—to changing operating conditions, such as wear or thermal deformation, contribute to achieving sustainable, highly performant, reliable and safe products. Researching the potential of such design elements requires systematic investigation of product properties.

Building on this, self-adaptive design elements stand apart from mechatronic systems by eliminating the need for external power sources or active control systems. This results in a lower system complexity, lower energy requirements for operation and greater reliability in practical use [28]. They are also easier to implement than mechatronic systems [29]. This reduces product costs, as the manufacturing costs may be lower due to the simplicity and the operating costs are lower due to the lower energy requirements [30, 31]. In addition, self-adaptive design elements fulfill a number of guidelines for sustainable development [32], such as reducing the number of materials and individual components used for production, reducing the energy required during service life, increasing service life and reducing service intensity during operation. Self-adaptive design elements therefore represent a promising alternative to mechatronic design elements, the development of which should be driven forward.

3 Principles of self-adaptivity

Having defined and classified self-adaptive design elements in the previous section, this section focuses on how such design elements can be realized with intent. Central to this is the understanding that self-adaptivity is achieved by deliberately tailoring the product-determining parameters, also known as the characteristics, of a design element, so that it responds appropriately to external influences without the need for external control. These characteristics—such as the position and arrangement of components within a system, its geometry, surface and material properties, and their distribution—are defined directly by the engineer and determine how the element behaves under changing conditions. The characteristics in turn give rise to properties such as weight, manufacturability and reliability, which cannot be directly influenced, but which emerge from the characteristics selected [33]. The characteristics can be modified across different scales—micro, meso, and macro [12, 34]—each of which is associated with distinct principles for implementing self-adaptivity.

At the microstructure level, the focus is on the material. At the macrostructure level, the emphasis is on the geometry of the system. This includes, on the one hand, the geometry of individual elastic parts, and on the other hand, the overall system, which consists of individual parts with defined geometries that interact kinematically. The mesostructure represents a transitional level between material and geom-

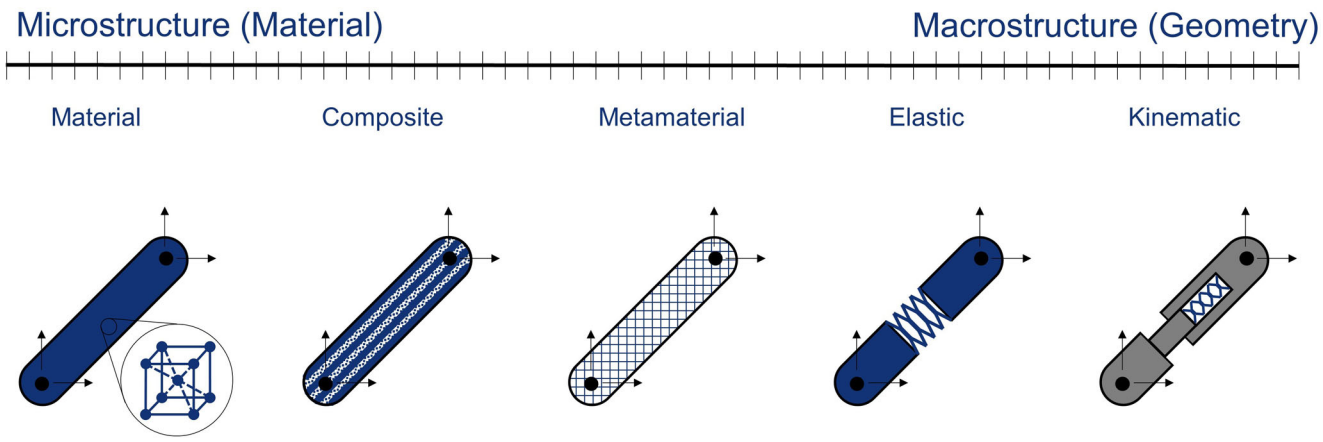


Fig. 2 Principles of self-adaptivity using the example of a truss element, arranged from microstructure to macrostructure level

etry, encompassing intermediate stages such as composite materials and metamaterials (see section Sect. 3.3 below). Self-adaptivity can be implemented at each of these stages, with all stages influencing one another.

These stages are illustrated in Fig. 2 using a truss element as an example, and they are explained in more detail below.

3.1 Materials

A very large selection of possible materials can usually be used to design a component [34]. Each material has specific properties due to its atoms and their arrangement (see Fig. 2), which can be used directly for self-adaptation. Already established materials, such as metals or polymers, are used for adaptation effects due to their specific properties. For example, the elastic behavior of metals and polymers can be used specifically for spring elements [35]. The viscoelastic behavior (which enables elastic deformation behavior in combination with damping properties) is advantageous for seals [36].

The properties of fluids can also be used for self-adaptation. One example of this is openers in greenhouse windows, which open and close automatically at a certain temperature due to the controlled thermal expansion of a fluid [37]. Another example is hydropneumatic suspension systems for cars, which combine the compression properties of gases with the favorable damping properties of hydraulic fluids [38].

In addition to established materials, smart materials are the subject of intensive research [39–41]. Comprehensive reviews of smart materials can be found in Refs. [42, 43]. Smart materials are characterized by the fact that they enable a controlled change in the system properties (such as stiffness or damping) and the system response (such as strain or shape) and thus cause an improvement in function or properties [39, 44]. Smart materials include shape memory alloys (SMA, react to temperature and pressure), piezoelectric materials (react to electrical voltage and pressure), electrostrictive materials (react to electric fields), magnetostrictive materials (react to magnetic fields), chromic materials (react to various stimuli), electrorheological fluids (are influenced by electric fields) and magnetorheological fluids (MRF, react to magnetic fields) [40]. These materials are often used in smart structures, but some are also suitable for self-adaptation.

Shape changes due to temperature and stress changes can be realized with SMA. Either the shape memory effect or pseudoelasticity is used [37]. They are often used in biomedical applications [45]. SMA wires are used, for example, in fixed orthodontic treatment, using pseudoelasticity to generate constant forces for large tooth movements after the wire is placed in the brackets [45]. MRF can be used for self-adaptive damping systems, for example [21].

Constitutive models are used to model the most important phenomenological properties of the material (such as hysteresis effects, elastic, viscoelastic, elastic-plastic) under external influences. The type of reaction represents the physical property of the material and is generally derived from experiments. None of the constitutive models is general enough to describe the material response under all possible circumstances, so the selection of an appropriate model is an important task in the modeling process. The right choice clearly depends on the type of material, but also on the loading conditions to be considered [46, 47].

Conventional materials offer a solid basis for self-adaptive systems, as their properties are well researched and established manufacturing and simulation methods exist. In addition, a wide range of processing methods enable broad adaptation to specific requirements, while their availability and cost efficiency make them economically attractive. However, conventional materials are subject to material fatigue and ageing, which can lead to a loss of function in the long term. Another problem is the limited possibility for self-adaptation.

On the other hand, smart materials are characterized by a high sensitivity to stimuli, a fast response to different conditions and a compact design [40]. However, the development of smart materials can be complex, and they can also be temperature-sensitive and expensive [41].

3.2 Composites

A composite material is a material system consisting of two or more phases at the macroscopic level and whose mechanical performance and properties are designed to be better than those of the individual materials of which it is composed [48]. The properties of composite materials are strongly determined by the intrinsic material properties of the individual components. Nevertheless, the geometric configuration, in particular the thickness and arrangement of the different layers and/or fibers, plays an important role and influences the overall behavior of the composite material. Many composites, especially fiber-reinforced plastics, are anisotropic, i.e. they have different mechanical properties in different directions.

A truss element made of composite material can be found in Fig. 2. Specific spring characteristics can be set by the specific arrangement of fibers and matrix.

One of the best-known applications of composite materials are bimetals, which typically take the form of a sheet or strip and consist of two or more materials, often of a metallic nature. Bimetals tend to adjust their curvature with temperature changes due to the different thermal expansion coefficients of the components [49]. In automatic starter systems of some gasoline engines, the air supply for the fuel-air mixture is controlled directly by the temperature of the supplied air. This control can be achieved by a bimetallic coil that positions the throttle valve in the intake air flow in such a way that the optimum fuel-air mixture is ensured at any air temperature [49].

Rigid thermal protection materials such as ultra-high temperature ceramics are desirable for applications in aircraft and spacecraft, but few materials can currently meet the emerging requirements for high temperature sealing of dynamic gaps caused by the unequal thermal expansion of different protective layers. However, composites can be specifically adapted for this purpose [17].

Composites are also used in architecture as hygroscopic, self-adaptive systems that react to fluctuations in air humidity. Composite materials are used that combine hygroscopic wood layers with passive materials. The change in humidity causes the active wood layer to expand or contract, which triggers a deformation of the composite [50].

The modeling of composite materials requires a detailed consideration of their heterogeneous structure. Constitutive relationships can be established for laminates using simplifying assumptions [51], allowing for an effective representation of their macroscopic behavior. Common approaches include classical laminate theory and finite element methods (FEM), which capture the anisotropic properties of the material.

Composite materials offer the great advantage of a flexible design, i.e. the composite structure can be customized according to the specifications of an optimal design [51]. This enables precise adaptation and enhancement of mechanical properties. However, from a sustainability perspective, composites remain a critical concern. If these materials can be burned as a recycling method without producing toxins, sustainability can be classified as good. However, composites are generally non-renewable and the problems of separating the different materials used in composites make these materials generally quite unsustainable [32].

3.3 Metamaterials

Metamaterials are a class of synthetically produced, mostly periodic structures that have unique mechanical, acoustic, magnetic or thermal properties [52]. They can be used to design new materials that do not exist in nature [53]. By arranging the architectural design of the lattice structures in specific patterns, metamaterials exhibit a variety of mechanical responses [20].

In the truss element shown in Fig. 2, for example, the spring characteristics is specifically adjusted by the metamaterial.

A subgroup of metamaterials are the auxetic metamaterials, which are characterized by a negative Poisson's ratio [54, 55]. This means that they become shorter in the transverse direction when they are compressed in the longitudinal direction, and vice versa [56]. An important technical application is vibration control [56]. Since most known auxetic materials have porous microstructures and the pore sizes of auxetic materials can vary during compression and tensile deformation, auxetic materials are considered to have significant potential for application in filters [57]. Auxetic materials can also be used in the medical field. A well-known example is stents, which are usually defined as small tubular structures that are inserted into the diseased region and mechanically support the damaged artery or serve to alleviate dysphagia in inoperable esophageal or gastric cancer [58, 59].

Other metamaterials have zero stiffness. Zero stiffness refers to a mechanical system or material that shows no resistance to deformation under an applied force [60]. This means that any displacement applied to the system does not increase the force. This property allows for easy deformation under mechanical load, making it ideal for applications such as vibration control, shock absorption, precise force control and adaptable structures. Potential areas of appli-

cation include manufacturing and industrial machinery and construction [20].

Design of metamaterials is increasingly using algorithms to determine the optimal geometry to fulfill a specific mechanical function, overcoming many of the limitations of traditional human-based design [61]. Metamaterials are analyzed using theoretical analyses, finite element simulations and experiments [57].

The properties of metamaterials such as increased shear strength and improved energy absorption are highly desirable. On the other hand, metamaterials often exhibit significant porosity in their geometric configuration, which often leads to a loss of desired mechanical properties. Thus, the benefit of the desired behavior, especially in applications such as energy absorption or protective devices, is significantly limited [57].

3.4 Elastic

Another option for self-adaptivity is the targeted elastic distortion of the components in order to set the desired deformations. For this purpose, the geometry is conditioned in such a way that desired deformations are enabled when a load is present and undesired deformations are suppressed [62]. Targeted elastic distortions, which generate desired deformations of components, have long been used to fulfill certain tasks. A well-known example of this are compliant mechanisms that generate deformations and thus transfer mechanical energy, convert and transfer forces and paths, and enable shape adaptation [63].

The adaptive truss element shown in Fig. 2 differs from the kinematic component in its design. The properties of the disk spring assembly are directly integrated into the component, making it a monolithic structure. Targeted elastic deformations can also be used, for example, in soft robotics as grippers that adapt to the shape of the object to be gripped [64] or for movement over irregular surfaces [65]. Examples of shape adaptation are compliant wings [66, 67] and antenna reflectors [68], which can adapt their shape to different prevailing operating conditions.

Self-adaptive systems based on elasticity are typically modeled as elastic continua. Their deformation response is always composed of desired and undesired deformations. Although these systems have an infinite number of degrees of freedom, they are specifically designed to emulate the kinematics of a system with few degrees of freedom (desired deformations). Precise modeling therefore requires a clear distinction between desired and undesired deformations [69].

The advantages include, in particular, the absence of clearance, friction and thus wear due to the possibility of producing monolithic components [70–72]. In addition, an internal elastic restoring force is generated during deformation by an external force, which results in a return to the undeformed initial state upon unloading. This means, for example, that separate return springs are not necessary [73]. Modeling is more difficult in comparison with the kinematic principle, as rigid body assumptions can only be used to a limited extent [74]. In addition, the purely elastic deformability is limited.

3.5 Kinematic

Self-adaptivity based on kinematic principles is achieved by the relative movement of rigid components of defined geometry to each other. The components are arranged in such a way that certain relative movements are enabled and others are restricted. Joints, bearings and guides, for example, can be used to restrict these movements.

This is shown as an example for an adaptive truss element in Fig. 2. The relative movement is enabled by a guide. In addition, a disk spring assembly is integrated to set a defined spring characteristic. Another example of a self-adaptive design element based on kinematic principles is the check valve. The check valve works mechanically via a closing element that opens in the direction of flow when the differential pressure is positive and allows the medium to pass. However, if the differential pressure is negative, the return flow of the medium presses the closing element against the valve seat and thus prevents the return flow. This principle enables automatic, passive flow control depending on the pressure conditions in the system [75]. The three-jaw chuck, as another example, centers a workpiece through a precise mechanical arrangement of its three clamping jaws. These jaws are connected to each other via a common mechanism, such as a thread or a gear rack. When actuated, all three jaws move simultaneously and uniformly towards the workpiece. Thanks to the synchronized movement, the workpiece is evenly enclosed from three sides and automatically positioned in the middle of the chuck. Even if the workpiece is not perfectly centered, the jaws adapt kinematically to the irregularities and thus ensure precise and stable fixing [76].

To analyze kinematics, such assemblies are typically modeled as systems of rigid links connected by ideal joints, an approach commonly used in multibody simulation. Elastic deformations are disregarded in this context. By neglecting elastic distortions, the kinematics can be precisely defined by a finite, usually small, number of scalar parameters, which determine the system's mobility [77]. This mobility is uniquely determined by the number of rigid components and the type and number of joints within the system [78]. Consequently, the kinematics can be derived purely from geometric relationships.

A key advantage of the kinematic principle is the availability of well-established design methods (e.g., the Digital

Mechanism and Gear Library [79]). Furthermore, system maintenance is simplified due to the interchangeability of individual components. However, the use of multiple moving parts also brings disadvantages, such as friction and wear during operation [80], as well as increased system size and the need for assembly. Implementing such adaptive structures on a micrometer scale also poses significant challenges.

3.6 Summary of the principles of self-adaptivity

The preceding subsections described five key principles of self-adaptivity—materials, composites, metamaterials, elastic, and kinematic. In each subsection, the principle was explained in terms of its function and implementation, selected general examples were provided, and the established modeling methods as well as the advantages and disadvantages of each principle were described. It becomes evident that all principles are well-established, with promising applications and thoroughly researched modeling approaches available for each. The practical realization and targeted design of advanced self-adaptive solutions, however, typically require the use of advanced analysis and simulation tools, such as finite element analysis (FEA). However, each principle possesses distinct strengths and limitations, making careful selection crucial depending on the intended self-adaptive function. In some cases, combining multiple principles within a single functional unit can further enhance adaptability and broaden the design possibilities. Yet, such integration requires careful consideration of the mutual interactions between principles, as these may affect the resulting behavior and overall performance. Overall, the application of these principles to design elements holds significant potential for advancing adaptive design.

4 Applications

Numerous efforts have already been made to enhance the functionality of design elements through targeted self-adaptation. While the previous section introduced the fundamental principles of self-adaptivity in general, the following will focus on their application to specific types of design elements, highlighting existing innovative solutions and examining their current level of adoption. The section is structured around selected groups of design elements that are particularly relevant for mechanical systems.

Each subsection begins with a brief overview of the respective design element. This is followed by selected examples of self-adaptive implementations, which may include aspects such as the underlying adaptation mechanism, constructional features, material choices, and applied design methodologies. Each subsection concludes with a summary of the range of available adaptive strategies for the given design element, their technological maturity, and remaining research gaps that must be addressed to fully exploit the potential of self-adaptive design elements in engineering practice.

4.1 Bearings

4.1.1 Journal bearings

Journal bearings are one of the most common design elements, which enable movement of machine parts under load relative to each other, based on the principle of sliding motion. In the field of journal bearings, a distinction can be made between bearings using an intermediate medium (liquid (e.g. oil) or grease), bearings with solid lubrication or without lubrication. Bearings with solid lubrication or without lubrication are only suitable for applications with limited sliding motion and load. In case of journal bearings with an liquid intermediate medium, a distinction can be made between hydrodynamic and hydrostatic journal bearings. In hydrostatic journal bearings, the separation of the surfaces is achieved by active control of an external oil pump. Due to the active control of the lubrication condition, measures of self-adaptation are of minor importance for hydrostatic journal bearings. For hydrodynamic journal bearings the pressure build-up of the lubricating film and the associated separation of the bearing shell and shaft is achieved by the relative movement between bearing shell, shaft and the acting force as soon as the lubricant is viscous enough and adheres to the surfaces. The simulative design of hydrodynamic journal bearings is usually carried out using elastohydrodynamic (EHD) or computational fluid dynamics (CFD) simulation. A lubricated contact is assigned to EHD if the elastic deformations of the contact bodies are equal to or greater than the lubricant film height [81]. If the deformations are smaller than the lubricant film height, an hydrodynamic simulation is often sufficient.

The robustness of journal bearings in the mixed friction range is significantly higher than assumed. Temporary mixed friction operation, e.g. in automotive applications (car engines with start-stop operation [82]), is less critical than previously assumed, as bearing surfaces have very good running-in properties. The same applies in particular to large bearings, e.g. wind turbines [83], because due to their mass, large bearings dissipate the frictional heat generated during running-in very good. Additionally, while mixed lubrication occurs only briefly during start-stop events in automotive combustion engines, large-scale applications such as wind turbines experience significantly longer residence times at low sliding velocities. Nevertheless, due to rapid running-in and higher heat dissipation, temperatures and wear rates remain acceptable. Thus en-

abling the successful application of journal bearings in wind turbines, even operated under wear critical start-stop conditions. Journal bearings have been able to replace roller bearings, significantly increasing the power density of wind turbine gearboxes [84]. Current research results also show that journal bearings do not require hydrostatic starting assistance even when used as main rotor bearings in wind turbines [85]. Accordingly, hydrodynamic journal bearings are suitable for applications, in which frequent start-up processes are part of regular operation and where a long service life is required. The operational safety design of hydrodynamic journal bearings in the mixed friction area is not covered by the established standards [86, 87]. As a result, safe operation under mixed friction conditions cannot be ensured by classical dimensioning approaches alone. This has motivated increased interest in additional safeguarding strategies, such as sensor integration for condition monitoring. The integration of sensors into the journal bearing volume wirelessly transmitting alerts to the machines' actuators [88], can only compensate design uncertainties by closely monitoring the bearing. An alternative strategy is the utilization of self-adaptive mechanisms in the design process that enable journal bearings to tolerate transient mixed lubrication without external intervention. Self-adapting design measures can, for example, influence the rigidity of the bearing structure, the behavior of the material under harsh conditions or the oil flow within the bearing and thus positively influence the tribological behavior under hydrodynamic and mixed friction condition. There are several review papers that examine specific advantages and disadvantages in operation depending on the choice of material or composite [89–91]. From these review papers, first conclusions on the self-adaptive behavior of different materials can be drawn. The main conclusion of these papers is, that the right material choice enables favorable tribological behavior in harsh conditions because of the self-adaption of the material to such conditions. Nevertheless, the papers do not use the term self-adaption. In addition to these existing papers, this paper not only considers self-adaptive behavior of materials (microstructure) or composites (mesostructure) but also gives an overview of the self-adaptive behavior of journal bearings with selected examples from the state of the art in research and industry from the micro- to the macrostructure.

Tilting pad bearings are a well-established type of journal bearing that exhibit kinematic self-adapting behavior at the macrostructure. For radial bearings, the bearing shell is divided into several partial sliding surfaces (segments). In contrast to conventional radial journal bearings, the shaft is not completely enclosed by the bearing shell surface. The sliding surfaces of the segments are arranged in a circular cylindrical manner and are pivotally supported on tilting points or axial tilting edges (see Fig. 3a). The principle of multi-surface journal bearings is also established for axial bearings. The self-adapting behavior works in such a way that the bearing clearance is adjusted by articulated bearing segments depending on the operating state so that favorable oil flow conditions are achieved. For example, due to the associated forces acting on the tilting pads the gap height changes to a smaller value at higher shaft speeds, which prevents the occurrence of turbulent flows and subsequent high increases in friction. The force equilibrium at the bearing segments, which lead to the self-adjustment of the clearance, can be calculated using the dimensionless Sommerfeld number [92].

The FlexPad-system represents an innovative concept for a journal bearing-based rotor bearing taking all radial, axial and tilting torque loads of the rotor implementing elastic self-adaptation at the macrostructure [93]. The concept uses segmented sliding surfaces with a double flexible support structure as shown in Fig. 3b. The segments are designed to ensure parallel displacement of the sliding surface under axial and radial loads as well as under bending moments. The flexibility allows the segments to adjust to the inclination of the shaft and avoid high pressure peaks due to edge loading. By avoiding edge loading and distributing pressure more evenly, the FlexPad bearing is expected to have a longer service life than conventional roller main bearings. Additionally, the segmented design of the journal bearing allows to overcome manufacturing and service cost challenges associated with large diameter roller bearings, since the segments are easy to dismantle and exchange.

Further examples of the application of self-adaptive design in journal bearings can be found in planetary journal bearings in wind turbine gearboxes. By geometrically adjusting the planetary gears, the rigidity under load at critical operating points is specifically changed. The resulting deformation causes a larger load zone with lower peak loads in a self-adaptive elastic manner. Planetary journal bearings in wind turbine gearboxes are exposed to high tilting loads, which mainly result from the forces generated in the helical gear mesh. The tooth forces cause a combination of radial load and moment load, which lead to complex operating conditions in the planetary journal bearing [94]. A design measure to improve the load carrying capacity of planetary gear bearings is the use of recesses in the form of milled pockets on the side walls of the planetary gear, which specifically influence the rigidity of the planetary gear [95]. The pockets incorporated into the planetary gear reduce the rigidity of the gear, thus enabling greater elastic deformability. Under load, the edges of the planetary gear's borehole yields significantly more with a hollowed-out gear than with a full gear. This intentional deformation leads to a wider load zone in the journal bearing and reduces the pressure peaks at the bearing edges.

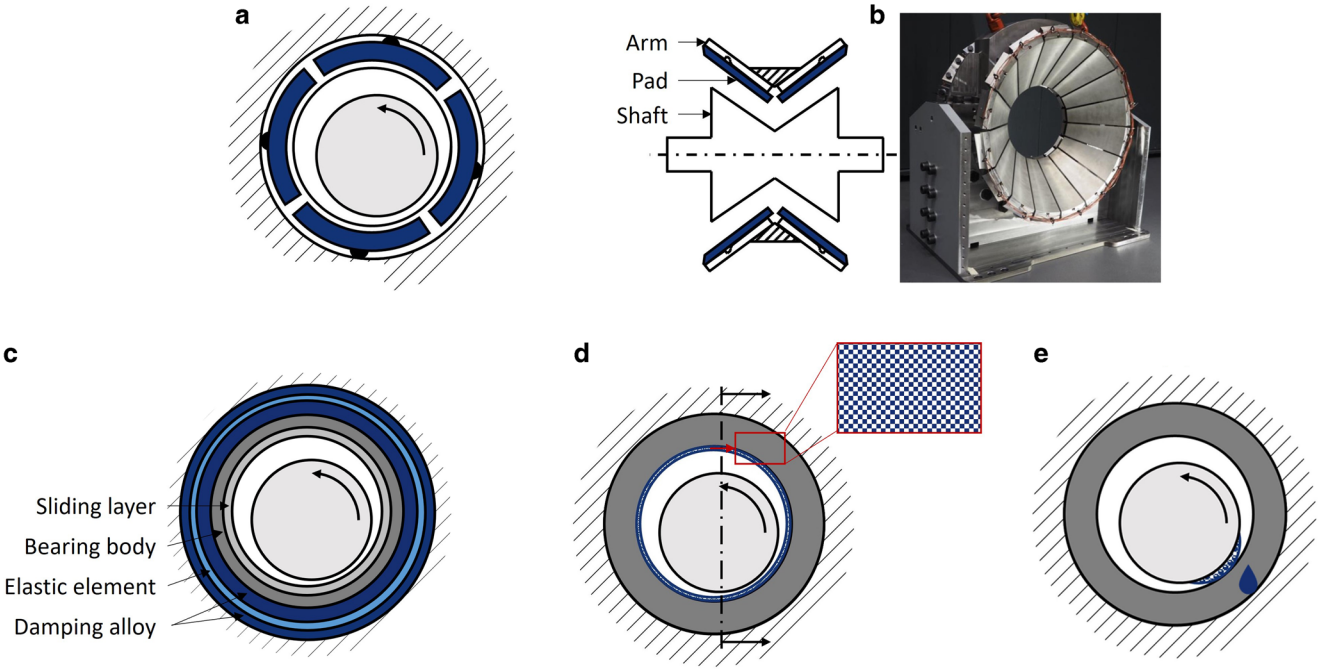


Fig. 3 **a** Tilting pad bearing, **b** FlexPad [106] (CC BY 3.0), **c** Self-adapting damping stern tube bearing [96], **d** Laser textured journal bearings, **e** Self-lubricating journal bearings

Another example of self-adapting behavior of journal bearings at the macrostructure (elastic-kinematic) is the work of Liu et al. [96]. The work presents a novel, self-adapting damping structure for water-lubricated stern tube bearings for maritime propulsion systems. The stern tube bearing consists of a synthetic rubber sliding layer applied to a steel bearing body. The self-adapting cylindrical structure around the stern tube bearing consists of two additional damping alloys (molybdenum and copper (Mu-Cu)) and an elastic element (silicone rubber). Figure 3c shows the structure schematically. Compared to conventional stern tube bearings, the contact load, wear and vibration damping have been significantly improved.

Kinematic self-adaptive designs for hydrodynamic journal bearings on the macrostructure include surface texturing of the running surface (see Fig. 3d). By texturing the running surface, the friction behavior and load carrying capacity of the journal bearing can be improved. The texturing is achieved by introducing small cavities into the bearing surface, e.g. by using laser ablation. Keshk et al. [97] were able to increase load carrying capacity and reduce operating temperatures by numerically optimizing the surface texture of hydrodynamic journal bearings. The most important effect of texturing the surfaces is creating turbulent flow in the boundary layer of the oil film [98]. By creating turbulent flows the heat transfer can significantly be improved [99]. The heat transfer behavior of the bearing is improved by the surface texturing, resulting in a lower operating temperature [97]. The lower temperature increases the viscosity of the oil and the minimum lubricating film thickness [100]. The increased lubricating film thickness compared to conventional plain bearings ultimately reduces the risk of damage-critical mixed friction. For textured journal bearings in start-stop operations, it was shown that they remained in the fluid friction zone for longer periods of time than conventional journal bearings under identical operating conditions. This is due to the kinematically, self-adaptively increased hydrodynamic pressure build-up even at low sliding speeds caused by turbulent flows [101]. As early as the 1980s, studies were published that examined the influence of turbulent flow on improving the thermal performance of hydrodynamic plain bearings [102, 103]. In their work, Wang et al. [104] were able to show that textures outside the load zone have a positive effect on the operation of plain bearings in fluid friction. The textures outside the load zone cause a local increase in gap height due to higher local hydrodynamic pressures caused by microflows at the textures. At the mesostructure to microstructure is the self-adaptation of journal bearings due to the use of specific composite materials with unique properties. For example, soft metallic materials such as tin can be used in metal matrix composites, which are released from the matrix under pressure, temperature and smear thus enabling additional dry lubrication. Furthermore, metallic journal bearings exhibit running-in behavior during operation in mixed friction, which represents self-adaptive behavior. A polished bearing surface is formed in the load zone where asperity contact occurs by smoothing out roughness and reducing pressure

peaks. A prerequisite for a smooth running-in process is the removal of wear particles out of the running track. The released particles must be permanently carried away from the plain bearing by the oil flow in order to avoid harsh three body abrasion. Additionally, by installing an oil filter, the released particles can be permanently removed from the oil circuit. Journal bearings optimize themselves adaptively through surface smoothing during operation. A prerequisite for this self-optimization through surface smoothing is that heat dissipation is sufficient. Sufficient heat dissipation during the smoothing process ensures that spontaneous failure of the plain bearing due to overheating is prevented. A key scientific challenge is therefore to design the heat dissipation of the journal bearing in such a way that the waste heat generated by the adaptation (running-in) does not lead to overheating of the bearing. A common bearing layer material is babbitt metal utilizing self-adaptive design measures, which melts under high thermal loads due to oil supply failure and thus protects the shaft from damage [105] (see Fig. 3e). This is in contrast to bronze bearings, which are also widely used and fail under heavy mixed friction conditions due to seizure and adhesive material transfer to the shaft. To date, the mechanisms and limits of the adaptation capabilities of the various materials, such as dry lubrication, running-in behavior and the formation of a polished surface due to roughness smoothening, have not yet been fully clarified. For a deeper understanding of the adaptive capabilities of different materials, local heat conduction, wear processes at roughness level and chemical interactions of reaction layer formation must be understood. However, their functionality has already been demonstrated on test benches.

In summary, a variety of self-adaptive designs for journal bearings are state of the art and research. These design measures range from the macrostructure and geometry of the bearings to the microstructure and associated material selection. At the macrostructure, self-adaptation occurs, for example, through targeted deformations by varying the stiffness of the journal bearing to increase the load carrying surface, improving the pressure distribution and subsequently reducing pressure peaks. Furthermore, kinematic self-adaptive behaviour is established at the macrostructure, e.g. tilting pad bearings. Trends such as the increasing substitution of roller bearings by journal bearings in wind turbines result in new operating conditions, where journal bearings have to withstand longer periods of mixed friction. Since the operational safety of journal bearings under mixed friction is not addressed by established standards, self-adaptive design measures become necessary to allow such operating conditions while ensuring reliable and safe operation. The future implementation of self-adapting design measures requires a significant amount of research. In particular, the mechanisms and limits of self-adaptability of journal bearing materials is still unclear. For example, the operating conditions at which the critical temperatures of the bearing material is reached are uncertain. There are no sufficiently accurate and detailed models to describe the material behavior in the event of an imminent damage. Physical models are required, in order to describe the local heat transfer and wear processes at roughness level or to describe chemical interactions during reaction layer formation and release of self-lubricating material particles. The emergency running behavior of journal bearings under mixed friction must be understood more precisely in order to be able to determine the limits of the adaptability of journal bearing materials. In combination with other self-adaptive measures, such as changing the local structural stiffness of the journal bearing, model-based design methods can then be developed which enable multi-criteria optimization of the journal bearing with criteria like reduced pressure peaks, increased lubricant film heights and improved heat dissipation and roughness smoothing during mixed friction. This multi-criteria optimization can further increase the reliability of journal bearings in highly loaded applications.

4.1.2 Rolling bearings

Rolling bearings are used for the transmission of forces and to enable relative movement between individual bodies [107]. Rolling bearings typically consist of two raceways and rolling elements arranged between them. In some designs, the rolling elements run directly on the shaft or the housing surface, depending on whether the inner or outer ring is missing. There are both full complement rolling bearings and rolling bearings in which a cage separates and guides the rolling elements. Rolling elements and races are usually made of chrome-alloyed steel or case-hardened steel, while the cage is made of brass, steel or plastic. They are divided into radial bearings and thrust bearings according to the load direction, or roller bearings and ball bearings according to the shape of the rolling elements. [108]

A large proportion of the rolling bearings used worldwide are catalog products. Naturally, the internal geometry of catalog bearings is designed in such a way that it represents a good compromise between long service life and low friction for a wide range of applications. The precise design of the internal geometry is the core know-how of the bearing manufacturer. A good example of this are the profiles of cylindrical rollers. These are designed in such a way that the load rating is as high as possible, but at the same time no edge pressures occur for the usual tilting from inner to outer ring. [109]

However, there are also many applications where bearings designed specifically for the application conditions are used rather than catalog bearings. In addition to the automo-

tive industry, examples include wind power, aerospace and railway. In these cases, the bearing geometry is modified taking into account the load cases and often also the elastic environment of the surrounding so that important criteria for the application (service life, rigidity, friction, etc.) are met. An example of this is Ref. [110], where structural optimization approaches are used to determine an optimum geometry for pitch bearings in offshore wind turbines. The pitch circle diameter, the nominal contact angle and the osculation are adapted so that the stresses in the contact are minimized.

Friction minimization is often the primary optimization goal. This applies in particular to the roller/rib contact of cylindrical or tapered roller bearings. In Ref. [111], for example, the hydrodynamic pressure, the lubricant film thickness and the friction coefficient in the contact are considered for various geometries. Further examples are given in [112–115]. What all these studies and approaches have in common, is that the geometry, like a profile correction for gears, can only form the optimum for one load situation or always represents the best possible compromise for a load spectrum.

These are only application-specific adaptations but not self-adaptive. There is hardly any research work or product solutions that deal with self-adaptive structures.

An existing product solution that specifically utilizes kinematic and elastic self-adaptive principles is the tube roller bearing presented in Ref. [116] (Fig. 4a). The bearing is designed to prevent slippage and thus ultimately smearing damage when the rolling elements enter the load zone. To achieve this, three cylindrical rollers with a slightly larger diameter are used in a conventional cylindrical roller bearing. At the same time, these rollers are designed as so-called tube rollers (hollow rollers) and are supported by a support roller in the inner bore. The slightly larger diameter tube rollers lead to a preload in the bearing and drive the bearing cage and thus the entire roller set at low loads. The bore of the tube rollers, on the other hand, ensures that at higher loads the enlarged rollers deflect slightly, and therefore do not have to carry any overload. The load is then distributed evenly over all the rolling elements, as in a conventional bearing. The support roller in the inner bore of the tube roller has a slight amount of radial clearance so that the tube roller can yield under higher loads. At the same time, it prevents excessive deflection of the tube roller. [116]

Patent [117] describes the design of outer rib guided cages for high-speed rolling bearings. Due to the high speeds, the cage expands as a result of centrifugal force. The solution presented in Patent [117] utilizes an elastic self-adaptive principle to adjust the targeted expansion.

Figure 4b shows a side view of the cage. The outer surface of the cage guidance is polygon-shaped, resulting in a guidance at the positions (2) where the diameter corresponds to the nominal guidance diameter (1). The cage should be guided in at least three positions. The diameter of the areas (3) between the guidance surfaces is smaller, which leads to an increase in radial clearance. Furthermore, additional masses (4) are attached in (3) so that a corresponding deflection of the cage takes place locally radially outwards. As a result, the guidance surface (2) is shifted inwards, which compensates for the expansion of the guidance diameter caused by the centrifugal force. The guide surfaces of the cage are designed with smaller radii of curvature, creating a narrowing gap between the bearing rib and the guide surfaces. A hydrodynamic lubricating film can form in this gap to guide the cage. [117]

The patent also describes the possibility of inserting a fiber winding (7) that is positively connected to the cage. The high modulus of elasticity of the fiber winding also limits the possible expansion of the cage due to the centrifugal force. [117]

Two approaches have been presented. The first prototype of the tube roller bearing has already been manufactured and tested. The polygon cage approach is based on a patent with uncertain commercial utilization. There is a very limited amount of research and product solutions dealing with self-adaptive structures in rolling bearings. As a result, there is considerable potential for further research, particularly in

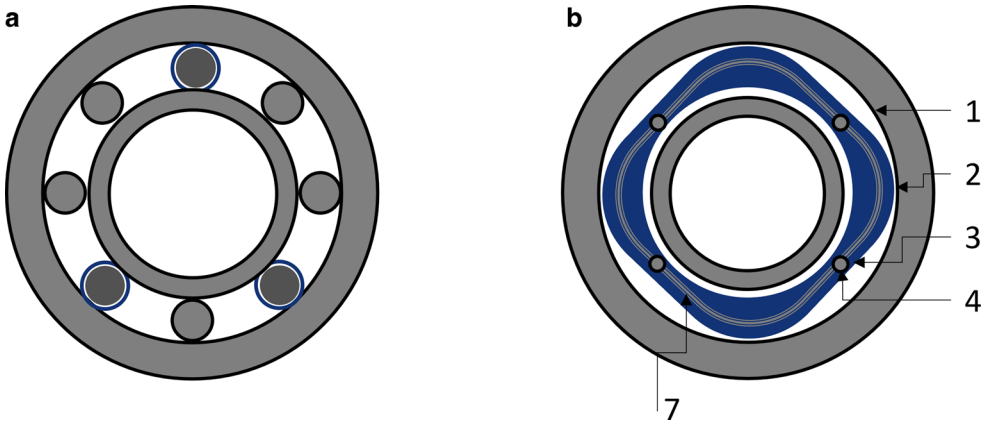


Fig. 4 **a** Tube roller bearing [116], **b** Polygon shaped cage [117]

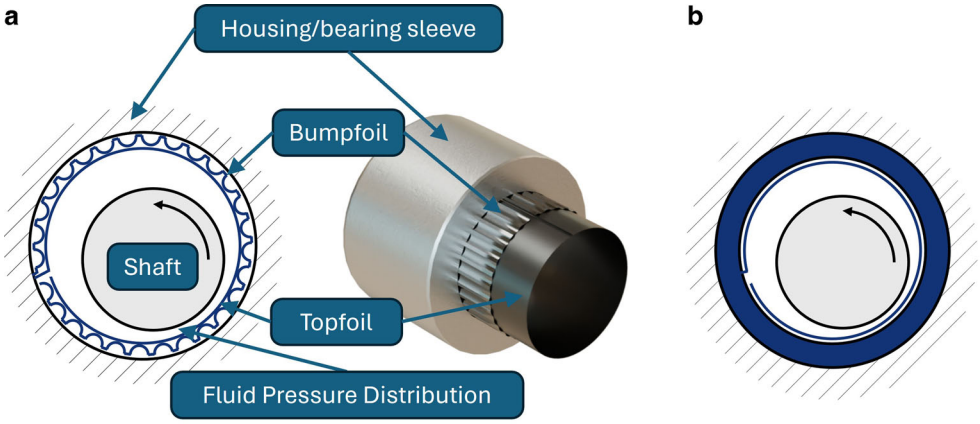


Fig. 5 **a** Sketch and picture of a gas foil bearing with self-adapting bump- and top foils; **b** Gas Polymer Bearing using self-adapting polymer layer and top foil

optimizing ring elasticity to improve load distribution and operational performance.

4.1.3 Gas foil bearings

Gas foil bearings are based to a large extent on the same principle of sliding motion as journal bearings. However, they use air or gases as the fluid and are therefore almost friction-free except for the run-up and coast-down phases. On the one hand, gas film bearings are only suitable for low to medium loads, mainly due to the lower viscosity of air respectively gases. On the other hand, unlike oils or liquids, air and gases offer a rising viscosity with increasing temperature, which is interesting for many technical applications. Typical applications for these air- or gas-lubricated bearings include air cycle machines and auxiliary power units in aviation, turbochargers and, more recently, air compressors for fuel cell technology. Due to its complete freedom from contamination, the gas foil bearing is currently the only possible passive and low-cost bearing type that can be used in the field of air compressors for a hydrogen-based energy supply using fuel cells. Figure 5a shows the basic design of a gas foil bearing. During operation, the bearing journal of the shaft floats in a narrow gap between the journal and a so-called top foil consisting of a metal alloy, often Inconel X-750 or stainless steel. Due to the rotation, a fluid pressure film forms, which ensures frictionless bearing operation from a mechanical point of view. The fluid film is supported on the elastically deformable top foil, which in turn is supported by a so-called bump foil, a corrugated, metallic, also elastically deformable foil. The bump foil is thereby supported on the rigid bearing housing.

This interaction of different principles of self-adaptivity results in a very effective bearing arrangement for small but extremely high-speed rotors with an unparalleled range of low to very high temperature applications. On the one hand, gas foil bearings, just like journal bearings, use the material properties of a fluid to build up a supporting film via a gap flow and thus use the material principle. On the other hand, gas foil bearings in their most common form use metallic foils, which allow elastic deformations due to their design and thus use the elastic principle. The elastic foils are primarily used to extend the operating speed range, which is limited in rigid gas bearings by unstable vibrations comparable to those known from the operation of journal bearings. A highly simplified analogy to tilting pad bearings makes this clear. The self-adaptive segments ensure stable bearing operation. The foils used in gas foil bearings stabilize the operating behavior with similar success. There are now a large number of foil designs that have been developed with a view to operational stability and lower lift-off speeds. Introductory overviews are provided by the works of HESHMAT AND HERMEL [118], AGRAWAL [119], SAMANTA ET AL. [120] and PRIYADARSHINI AND BEHERA [121]. There are also alternatives to the elastic metallic bump foils. Polymer film bearings, for example, use a polymer layer underneath the top foil instead of the bump foil, which corresponds to the material principle of self-adaptivity, see Refs. [122, 123] (Fig. 5b). However, the elastic principle is also retained, as the top film with its elastic properties is still used.

The current variance of gas foil bearings in the area of self-adaptive design elements is already quite large with the elastic films of different designs, the use of different fluids such as air or other gases and the use of elastomer materials. However, an overall view of the principles of self-adaptivity reveals further interesting design possibilities that could ensure more optimal and reliable operation of gas bearings. For example, the use of metamaterials would be interesting for research Fig. 2. In addition, there is a lack of a methodical approach to the development of gas bearings with regard to the principles of self-adaptivity. This results in a further research objective of a methodically based development of these bearings, taking into account the design elements mentioned, depending on the respective requirements for the bearings.

4.2 Seals

Seals are design elements that are used to prevent or limit the leakage of fluids through a gap between two sections of a machine with or without relative motion between these sections. Although there exists a large variety of seal types, they can be broadly classified into clearance seals and contacting seals.

Examples for clearance seals are labyrinth seals, centrifugal seals, floating ring seals or brush seals. Contacting seals can be sub-classified into static and dynamic seals based on whether there is a relative movement in the gap that is to be sealed. Examples for static seals are o-rings and gaskets, whose sealing function can only be guaranteed if the contact pressure between seal and counter surface is bigger than the differential pressure [124]. Rotary seals such as rotary shaft seals and mechanical seals and translational seals such as piston or rod seals are dynamic seals. They usually provide an active sealing mechanism that prevents or limits the leakage through the lubrication film forming between the relatively moving parts. Due to its hyper- and viscoelastic behavior, many seals are partly made out of rubber but many other materials such as polymers, carbon, steel or ceramics are also used. [125–127]

Seals must self-adapt to different imperfections and disturbances, such as shape and size deviations and roughness of the counter-surfaces, variations in compression or in the operational conditions. In many cases, this self-adaptability is achieved by either the elastic compliance of the material or component (rubber, springs) and/or by the shape of the seal.

There exist many examples of self-adaptability in seals, both in outdated or state-of-the-art applications and in research prototypes. Static seals typically prevent leakage passively by being compressed and deforming in such a way that geometry deviations and roughness of the contacting surfaces are being filled with the seal material to close leakage channels. Furthermore, they are also able to adapt to changes in the gap geometry, for example a widening of a hydraulic cylinder due to the operating pressure or generally thermal expansion. Consequently, static seals can be classified as self-adaptive design elements, since they are able to compensate such changes due to their hyperelasticity.

Some dynamic seals also act self-adaptively. For example, a rubber rotary shaft seal is shaped in such a way that its membrane can bend in order to adapt to shaft oscillations or misalignment (elastic self-adaptability) [126, 127].

Axial seals, on the other hand, rotate on the shaft itself and reduce the axial load on the static counter-surface with increasing shaft speed due to centrifugal forces [126]. At even higher shaft speeds they lose contact and become a (almost frictionless) flinger seal. This can be interpreted as a elastic self-adaptation of the sealing mechanism to the shaft speed.

In mechanical seals the rotating face is being pressed onto the stationary face by a spring, which allows them to elastically self-adapt to wear of the sealing faces [125].

Translational piston seals have to seal against high pressure differentials which cause a widening of the cylinder, creating the danger of the formation of a gap between seal and cylinder. This is often mitigated by the use of an energizer that presses the seal against the cylinder wall. Some energizers are self-adaptive, for example an o-ring that uses the incompressibility of its rubber material to translate its loading from the pressure into an outwardly acting force on the seal that increases with the acting fluid pressure (use of both elasticity composites for self-adaptation) [126, 128].

Another example of self-adaptive seals are floating self-concentric seals, which are designed to accommodate eccentricity in rotating machinery. These seals dynamically adjust their position in response to pressure differentials, enhancing their sealing performance even in the presence of shaft misalignment or other variations in the system (kinematic self-adaptability). This adaptability ensures more efficient operation and minimizes wear, making them suitable for high-performance applications like turbomachinery [129–132].

Besides these self-adaptive functions of common state-of-the-art seals, there also exist further examples for the use of self-adaptability in the context of seals. A proof of concept study shows the possibility of using using SMA for seal energizers, allowing an adaptation of the seals radial force to different operational conditions (Fig. 6a). SMA exhibit a shape shifting behavior at their austenite finishing temperature. The SMA material NiTiCu with an austenite finishing temperature of 60 °C (±5) was used in the related study to induce a shrinking of the energizer (SMA wire). In the studied case the SMA was activated using an induction heater but applications where it reacts to the lubricant/medium temperature in order to mitigate the temperature-induced loss of radial force from the rubber part are also possible (metamaterials). [133]

In wellboring applications, highly pressurized fluids are used to stabilize the drilling hole and flush out debris. This is hindered if leaks occur. In order to provide a self healing mechanism in wellboring, pressure activated sealants (PAS) are used that phase transform from liquid to solid under differential pressures in leaks due to shearing, deformation and adhesion—similar to blood coagulation in wounds—and thus plug the leaks. This behavior can also be characterized as self-adaptive. [131, 134]

In personal protection equipment for space applications, seals must work under different pressure differentials and must be easily and quickly assembled. In order to achieve this goal, a hollow sealing ring with a pressure equalization

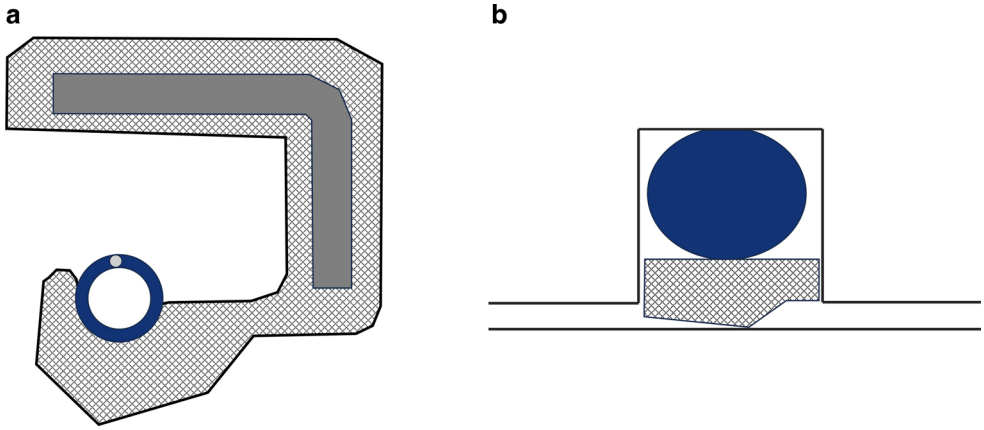


Fig. 6 Self-adaptive seals: **a** radial shaft seal with SMA energizer [133], **b** rod seal using a rubber energizer to compensate the working pressure in the sealing contact

gap that allows the sealing force to increase with increasing differential pressure is used by [124]. The self-adaptability to differential pressure is based on the seal shape and is thus elastic.

Summarizing, one can establish that (self-)adaptation is a crucial element in the working principle of most seals and is therefore widely used. Future potential for improvement of sealing systems lies especially in the use of SMA (metamaterials).

4.3 Couplings and clutches

This subsection reviews generally design elements that are used to connect or disconnect shafts within technical systems. Thereby, its distinguished between design elements, which connect two shafts permanently, coupling, connect and disconnect two shafts in an on/off fashion, switchable coupling, or transfer torque under slip, clutches. In addition to the loads and torques to be transmitted, the system requirements, for example regarding misalignment, start-up, and vibration behavior, must always be considered when selecting the coupling or clutch to be used. In addition to the pure connection function as well as compensation and damping, clutches perform functions such as defined switching (controlled clutch) or safety limits of the transmission (safety clutch). Purely connecting couplings are often referred to as "constants". Rigid couplings, which only ensure a fixed connection between the shafts, are also called blind couplings; these include, for example, flanged or sleeve couplings. However, there are compensating couplings that are used to connect shafts with slight deviations in position (axial, radial, angular). These include gear couplings and chain couplings, for example. Flexible couplings are often used, which also absorb overloads and dampen vibrations, such as elastomer couplings or flexible pin couplings. In addition, other special coupling types such as fluid couplings [135] or magnetic couplings [136, 137] exist. In the case of switchable couplings, a further distinction can be made between controlled and self-controlled clutches. [35, 138, 139]

In this review, self-adaptive couplings or clutches are defined as follows: Self-adaptive mechanical design elements that autonomously adjust their functional response, such as stiffness, damping, or torque transmission, in real time and under varying operating conditions, without external control systems or reconfiguration after installation. While brakes are nothing else than couplings and clutches with one of the shafts fixed.

The abovementioned definition excludes components that:

- Require external energy input or control logic (e.g. magnetorheological systems with active magnetic fields).
- Exhibit preset, non-responsive behavior after initial adjustment (e.g. manually pressurized pneumatic elements).
- Adapt only at the system level through external actuators or changes in boundary conditions.

Apart from the rigid couplings and externally controlled clutches, most couplings and clutches already exhibit self-adaptive behavior. They can be differentiated as follows according to the underlying mode of operation:

- Load-dependent torque transmission: Nonlinear contact behavior or frictional elements enable variable torque limit.
- Elastic deformation: Structural compliance passively compensates for misalignment or overload.
- Damping: Passive materials or geometries dissipate energy without external input.
- Geometric responsiveness: Designs that redistribute stress or deformation paths under load, e.g., compliant geometries or metamaterials.
- Inherent safety adaptation: Structural failure elements (e.g., sacrificial bolts) that respond predictably to overload.

This extends beyond the design for specific operating conditions, aiming to ensure optimal performance, maximum service life, and improved operational behavior across a wide speed range or under varying temperatures, for instance. Some examples of adaptive behavior in couplings with different mechanisms are shown below:

A comparatively simple type of self-adaptation consists of designing the elastic and partly non-linear material behavior of fixed coupling components for the expected load case. For example, the non-linear behavior of claw couplings can be predicted by simulation [140–142]. Simulation tools also exist for bolt couplings to design the response behavior of the coupling depending on the load [143]. Experimental work on the dynamic stiffness of such couplings also exists [144]. An analytical model for describing flexible couplings can be found, for example, in Ref. [145]. Approaches that model the response behavior of the coupling in the entire drivetrain go even further [146].

To overcome the limitations of typical materials in flexible couplings, there are also approaches to using magnetorheological elastomers to adjust stiffness and damping behavior to the operating point via an external magnetic field [147]. A similar approach can also be found in [148], where the coupling was used on a powertrain test rig to dampen vibrations. However, according to the definition in this article, this is not a self-adaptive system.

Even though solid bodies are most used for coupling applications, alternative coupling concepts offer greater potential when it comes to self-adaptation. By using pneumatic damping elements, for example, the stiffness can be specifically adjusted via the air pressure [149]. If the pressure is only set once for the application, the principle can be regarded as self-adaptive (see Fig. 7a). Alternatively, active control would also be possible. Kinematic couplings that are used for exact positioning can also be used specifically for compensation purposes via a pneumatic system [150]. Fluid couplings, in which the power transmission takes place via the flow of the fluid, are often used especially for start-up processes and strongly varying loads. The dynamic behavior can be influenced by the specific design of the turbine components and the fluid. A numerical or theoretical design is often used here [135, 151].

In regards of safety management, clutches may play an important role in various applications, such as marine shear-element clutches [152], there the clutch must ensure safety requirements. In this example the bolt design in the break away system plays a crucial role in its effectivity and thus, allows a certain degree of self-adaptivity by an optimal shape design, as limits set by safety requirements can be implied via the bolt design in the break away system can. Further, when vehicles with internal combustion engines start rolling clutch engagements sometimes generate judder, potentially harnessing components on the drivetrain. As the judder mostly occurs in form of torsional vibrations it is suspected to be caused by stick-slip processes at the interface of the clutch friction disc and the flywheel [153]. Identifying a smart material pairing in the layout of the frictional lining may thus be utilized to mitigate these judder effects. The selection of the optimal shape and material of the clutches additionally shows a significant influence on the torque carrying capacity, the wear rate, and the contact temperature [154]. When considering wet clutches, exclusively used inside automatic gearboxes and common in drive-trains of motor bikes due to their more stable performance and smoother torque transmission, the selection of the lubricant—in particular in the centrifugal effect—in combination with the permeability of the friction material can control the dynamic characteristics of the engagement time and relative speed of the wet clutches to a certain extent [155]. Thus, the shape of the clutches components, as well as the material of its constituents, is destined to be utilized for self-adaptivity and widely applied to achieve certain specific characteristics in the clutch system. Further remarking, that a brake the same as a slipping clutch with one of the shafts not rotating, thus all the above mentioned about clutches applies to brakes as well.

Table 1 highlights key physical principles such as elastic deformation, nonlinear material response, or hydrodynamic effects that enable passive, autonomous adjustment to operating conditions. Couplings relying on preset conditions

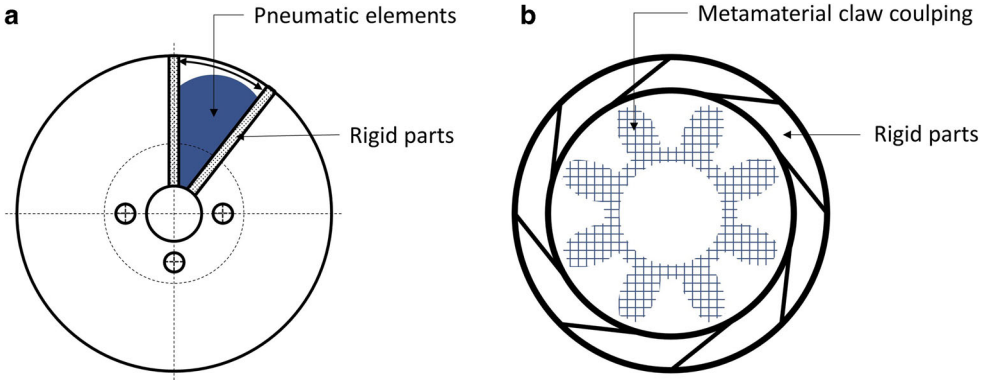


Fig. 7 **a** Pneumatic coupling [149], **b** Elastic coupling with metamaterial

or external control (e.g., pneumatic or magnetorheological systems) are explicitly excluded or marked as borderline. This classification underscores that self-adaptivity in couplings can emerge from a wide range of passive design strategies, but also emphasizes the importance of clearly distinguishing them from actively controlled systems.

In summary, the self-adaptive behavior of the clutches is already crucial for their function. The main principles of self-adaptivity are a targeted selection of materials as well as elastic and, in some cases, kinematic concepts. We see great potential for future research, especially in the use of optimized composites and metamaterials for application (see Fig. 7b) to extend the degree of self-adaptivity beyond the behavior of pure materials. Using topology optimization approaches, we also see the possibility of developing elastically compliant couplings that can adapt even better to specific load conditions.

4.4 Springs

Springs, especially self-adapting springs as design elements represent an innovative area within the design and optimization of machine elements. Unlike traditional springs, these springs can and could adapt their stiffness and damping characteristics in response to changing loads, frequencies and temperatures, without requiring external control inputs. This self-adaptation capability can significantly simplify and improve performance, durability, and energy efficiency in various mechanical systems, from automotive suspensions to industrial machinery.

Self-adapting springs can use various physical principles to achieve adaptability. These include

- variable geometry, where springs deform to modify load distribution based on applied force such as torsion-bending-coupling;
- smart material properties, such as SMA [156] and composites with nonlinear elasticity;
- materials with frequency, temperature or time dependend properties and
- structural optimization, where designs distribute force asymmetrically, resulting in variable stiffness over a range of deformations.

Each mechanism offers unique advantages and limitations depending on the application requirements, such as load capacity, durability, response time and temperature.

One prestigious example for this adaptability was investigated for wind turbines within the research project SmartBlade [158, 159]. The turbine blades as design elements, seen as leaf springs, are subjected to bending loads, which depend on the wind pressure. A new kind of mechanical layout allows the blade's pitch angle to adapt to the wind speed. Therefore, the composite wing blade is specifically designed with a non-symmetric fibre layup, leading to so called bending-torsion-coupling (see Fig. 8a). For increased wind loads, these new blades will adaptively twist the wing section to reduce lift and drag of the wings and also the loads of the whole structure. The self-adaptation reacts instantly, especially necessary in gusty conditions, where conventional mechatronic rotation systems can only work with a time delay. In addition, this twist can adapt in the longitudinal direction, which is not possible with conventional wings. Overall, these self-adapting blades allow the working area to be extended to high and uneven wind loads without having to switch off the turbine.

In addition to understanding a spring as a single design element, the definition can also be extended to spring systems consisting of several different springs, that can be activated at different load or deflection situations, or even spring and damper combinations, especially using gaseous or liquid substances. For example, Borosiloxane is a non-Newtonian fluid, whose viscosity reacts depending on the

Table 1 Classification of reviewed couplings and clutches by self-adaptive mechanism

Design Element Type	Mechanism of Adaptivity	Adaptive Feature	Meets Definition?	References
Claw Coupling (nonlinear)	Material deformation under load	Load-dependent stiffness	✓	[140–142]
Bolt Coupling	Structural deformation	Load response, overload protection	✓	[143, 144]
Flexible Pin Coupling	Elastic deformation	Misalignment compensation	✓	[145]
Fluid Coupling	Hydrodynamic torque transmission	Torque-speed adaptation	✓	[135, 151]
Shear-element clutches	Sacrificial bolt geometry	Overload protection	✓	[152]
Wet Clutch (passively optimized)	Friction material + lubricant properties	Judder mitigation, smoother engagement	✓(if passive)	[153–155]
Pneumatic Coupling (preset)	Static internal pressure	Stiffness adjustment (pre-set)	x/borderline	[149, 150]
Magnetorheological Coupling	Externally controlled magnetic field	Adjustable damping	x (active system)	[147, 148]

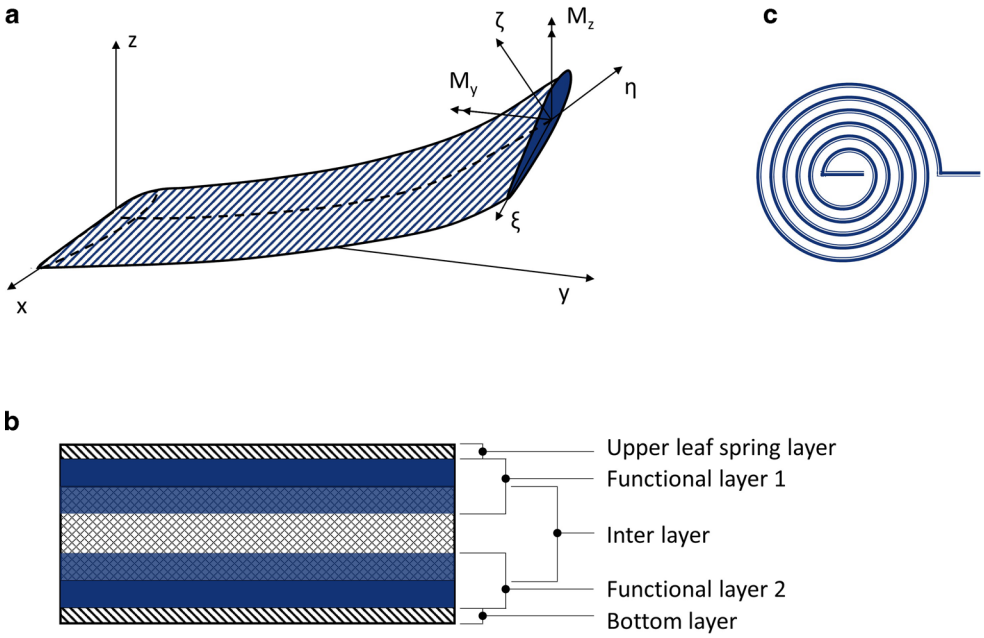


Fig. 8 **a** Self-adaptive wind turbine blade with bending torsion coupling [157]; **b** Design of the innovative multi-layer structure. The layer structure consists of an upper and lower carrier layer, with a first functional layer and a second functional layer in between. Both functional layers can be partially or completely penetrated by an intermediate structure. The carrier layers can be made of different materials (metal, plastic, etc.), and functional layer 1 can also consist of a borosiloxane with different material parameters than functional layer 2 (softer/harder), **c** Bimetallic spiral spring

duration of the load. For short-term impacts, it shows predominantly elastic behaviour, but due to increased load exposure time, the reaction of Borosiloxane changes to viscoelasticity with high damping and deformation potential. [160–162] Various materials (plastics, metals, organic compounds, etc.) and structures (fabric structure, honeycomb structure, foams, etc.) are conceivable for the intermediate structure. Preliminary work on the design of the multilayer structure has been carried out in Ilmenau (see Fig. 8b). A systematic design methodology for the multi-layer leaf structure and the spring types to be manufactured from it (leaf springs, coil springs, disc springs, etc.) and the solution of technological problems are still required. The material characterisation of borosiloxane has been carried out using rheological tests (frequency and amplitude tests) [159]. The mechanical properties of the shell structure (both carrier layers) can be combined in many ways with the viscoelastic properties of borosiloxane. The promising potential of this multilayer structure (MLS) results from the phenomenon that the novel MLS behaves predominantly elastically under 'short-term' loading and increasingly viscously under 'long-term' loading. With regard to the variable mechanical time constant, a wide range of applications are conceivable, for example as special energy-free self-adaptive switches, sensors or frequency-dependent coupling elements.

In addition to changing load or deflection environments, other principles can also be used for activating the adaption. Changes in operating temperature lead to adaptions in material stiffness, damping and residual stress. For a long time, leaf springs are used as bimetal switches [163, 164], changing the beam curvature in dependence on temperature. Bimetallic spiral springs can passively operate for decades in thermometers, heat controls and safety switches to temperature-dependent adapt spring characteristics (see Fig. 8c). [165]

Furthermore, shape memory alloy-based spring and actuator systems have been successfully established on the market for various applications, as they offer self-adaptive characteristics depending on temperature. They have high working density, are simple in design, operate silently and have lightweight construction potential. Different material dependent effects can be used. Possible applications include air conditioning systems for buildings and vehicles, and medical technology.

Current applications of self-adapting springs in design elements demonstrate their versatility. In industrial machinery, springs are used in vibration damping systems that adapt to fluctuating operational loads, reducing wear and maintenance needs. In robotics, self-adaptive springs in joints and actuators could enable smoother movement and improved load distribution in robotic limbs and exoskeletons.

Several areas for future research have been identified, including the development of new composite materials to increase adaptability and durability, innovations in computational modelling to optimize spring geometry and predict performance under different loading conditions. Self-adapting springs offer the opportunity to improve the performance and sustainability of design elements in various industries. Overcoming current limitations through material innovation and advanced design will enable wider acceptability and open up new application possibilities.

4.5 Dampers

Dampers are used for energy dissipation, i.e. they absorb kinetic energy and convert it into other forms of energy. This allows them to reduce longitudinal, transverse or rotational movements. In most cases they reduce vibrations. Normally, dampers are used to either dampen velocities or directly reduce displacements. Dampers are often tuned to specific resonance frequencies in order to specifically reduce vibrations in these ranges [166]. Outside this narrow frequency range, however, the damping effect can decrease significantly as the system is no longer optimally tuned to the vibration characteristics. This type of selective damping is only effective when undesirable vibrations occur within a limited frequency band.

Self-adaptive dampers are designed to adjust their damping behavior intrinsically in response to changing vibration conditions. Unlike conventional dampers that target fixed resonance frequencies, self-adaptive dampers aim to maintain effective performance across a broad frequency band. This is particularly advantageous in applications where the dominant vibration frequencies vary over time, such as in machines and vehicles with changing operating conditions, buildings exposed to wind or traffic-induced vibrations, or systems for noise and sound reduction.

Various forms of self-adaptivity are used to extend the frequency band to be covered. One possibility to compensate the disadvantages of a specific damper system is to combine multiple different systems, like displacement dampers with fluid dampers or viscoelastic dampers and friction dampers, with each other. These so-called hybrid dampers, i.e., dampers consisting of a combination of several individual dampers, were compared in the review article by ARVIND AND SANTHI [167].

In the case of self-adjusting dampers, for example, the adjustment of the frequencies to be damped plays a central role. An example for this are tuned mass dampers (TMD) which consist of (i) a secondary (auxiliary) mass, (ii) a spring and (iii) a viscous damper [166, 168]. These TMD can dampen vibrations by converting energy between the structure, whose vibrations are to be dampened, and an auxiliary mass. Classic TMD are not 'self-adaptive' as they are only tuned to one fixed frequency. Furthermore, the tuning can degrade over time [168]. As a solution to this problem, so-called intelligent TMD have been proposed, in which either the stiffness or the damping can be adjusted [168]. An example of such smart TMD are pendulum TMD in which the oscillating secondary mass is a pendulum, cf. Ref. [166]. The length of the pendulum influences the eigenfrequencies and thus the frequencies of the base structure which can be damped (see Fig. 9a). In principle, self-adaptivity can be achieved by adjusting the pendulum length during operation, thereby retuning the damper to match changing excitation frequencies. However, only suggestions are made on how exactly the length can be adjusted, for example by passively changing the stiffness of the connected spring. COLHERINHAS ET AL. [166] presented a numerical model for the design and optimization of pendulum TMD for the use in wind turbines attached to the nacelle.

Due to their special topology and geometry, metamaterials reduce the amplitudes of vibration waves that pass through them, which leads to effective damping of the vibrations [172]. The complex architecture of metamaterials results in a large band gap that allows vibration isolation for

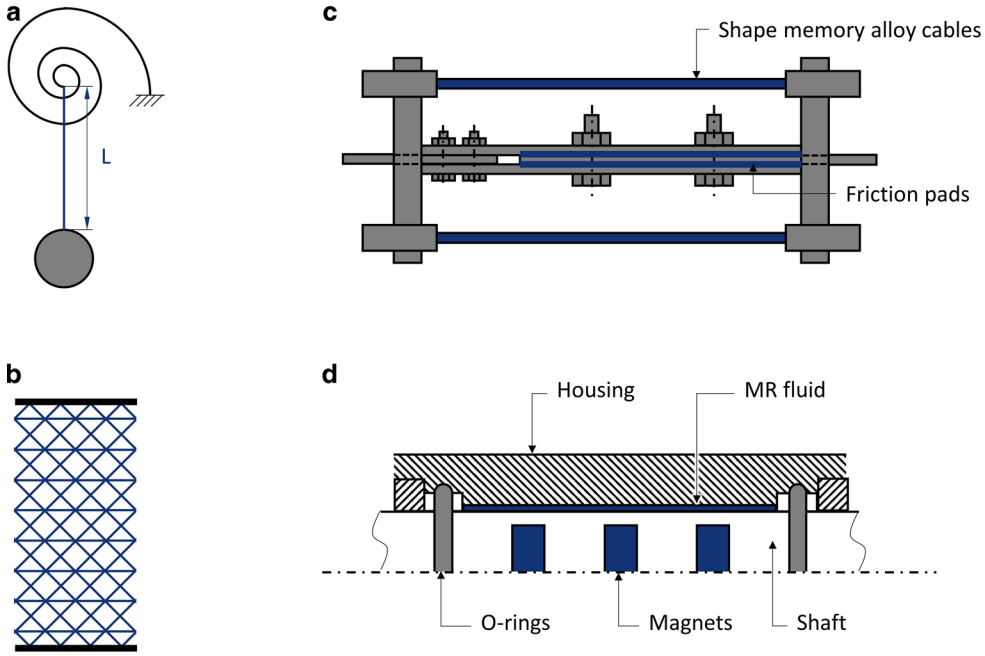


Fig. 9 Self-adaptive dampers: **a** Pendulum TMD [166], **b** Metamaterial [169], **c** Hybrid damper [170], **d** Damper with MRF [171]

a wide frequency range [173]. Metamaterials allow an integrated design, as the vibration dampers are embedded in the main structure and not attached as an additional component [173]. DYKSTRA ET AL. [169] show that buckling metamaterials have a high potential for vibration damping (see Fig. 9b). They point out that these buckling-based structures effectively dampen vibrations regardless of the type of excitation—whether controlled or random. The authors also suggest that this method could in principle be suitable for limiting the transmission of any vibrations. An elastic metamaterial with very good damping performance was introduced by coupling snap-through and pseudoconstant force behavior in Ref. [174]. The proposed meta-damping mechanism operates independently of global or local resonances, making it particularly beneficial for multi-mode applications and eliminating frequency band restrictions. DALELA ET AL. [173] present a comprehensive overview of various metamaterials for vibration control. They emphasize that many of the designs discussed have been investigated both theoretically and numerically. Advances in 3D printing technology are expected to be crucial for the experimental implementation and performance of practical tests on the fatigue behavior of these materials.

The application of smart materials—such as SMA—is another possibility for self-adaptive dampers. In SMA, the pseudoelastic hysteresis, the transient damping effects in the two-phase state and the damping capacity of the martensitic phase are specifically utilized. The damping performance can be optimized based on factors such as temperature, strain amplitude, frequency, alloy composition, and thermomechanical treatment [175]. TERRIAULT ET AL. [176] presented a damper which is made of multiple SMA wires for use in small residential homes for earthquake protection. One end of the wires is fixed, while the other end is connected to a movable part. If the wires are loaded via compression forces, the fixed end can slide into a fixed support structure. Due to the inherent hysteresis, energy is dissipated via the loading and unloading curves, which is used to dampen the load on the building. A decisive aspect in the design of dampers for buildings that are intended to withstand earthquakes is, in addition to damping, the self-centering capability. This describes the ability of a building to return to its original vertical position after a seismic event. ASFAW ET AL. [170] develop a novel hybrid damper by combining the pronounced self-centering ability of SMA cables with the non-sacrificial energy dissipation of a friction damping mechanism, see Fig. 9c.

BUI ET AL. [171] described the use of MRF, for the design of a self-adaptive damper for the application in washing machines, see Fig. 9d. The damper consists of a shaft with three permanent magnets at both ends, i.e. six permanent magnets in total. The housing for the MRF, which is in contact with the shaft, is located in the center. In the default configurations, the permanent magnets are located outside of the housing containing the MRF. Therefore, if no vibrations occur, there is no interaction between the permanent magnet and the MRF. However, for vibrations with higher displacements, the magnets enter the housing, so that the interaction between the MRF and the permanent magnets leads to an increasing viscosity of the MRF. This increase in viscosity—due to friction—produces a damping force. The higher the oscillations and the further the permanent magnets are pushed into the housing, the greater the damping force becomes. Different commercially available MRFs were used in the study. The shaft, the housing, and the pole pieces were made of C45 steel. Permanent magnets are disc-shaped and made of NdFeB grade N35, cf. Ref. [171]. The design of the damper was numerically optimized using ANSYS and a prototype was manufactured and tested under real conditions, i.e. inside a washing machine.

The state of the art in self-adaptive dampers shows that there are already numerous innovative approaches. However, most of these are still at a theoretical or experimental level and are not yet directly suitable for practical application. One of the reasons for this is that not all possible influencing factors, such as temperature effects [177] or fatigue behavior [173], have yet been sufficiently investigated.

With the formulation of comprehensive standards for the development and subsequent use of such self-adaptive dampers, their use in practical applications will increase significantly.

The possibilities for the use of self-adaptive dampers given in the literature are manifold: (i) better protection against earthquakes and (ii) applications in harsh environments such as offshore wind farms, to name only a few.

4.6 Housings

The housing serves as the enclosing structural component, designed to fulfill several critical functions. Its primary purposes are as follows:

- Transmitting forces from the bearings to the supporting foundation.
- Ensuring precise alignment and positioning of drive train components, specifically bearings, shafts and gears.
- Facilitating heat dissipation to maintaining optimal operating temperatures.
- Attenuating noise, vibration and harshness (NVH).
- Isolating the drive train from external contaminants (for example, particulate matter) to protect both the internal components and operating personnel from potential hazards.
- Preventing loss of fluids/lubricants.

These functions need to be achieved while maintaining a design that is lightweight and facilitates easy assembly

and disassembly [178]. However, lightweight construction usually leads to noise and vibration issues [179].

While some of the aforementioned functions do not necessitate adaptation in accordance with the operational status, others, such as sound attenuation, are best served by adaptive adjustment. The application of an external vibration that superposes destructively with the vibration of a gearbox, known as active vibration control, has therefore been a subject of research for quite some time. The control concepts differ in the manner in which the actuation force is applied. For example, an additional bearing may be employed [180, 181], supporting struts of the gearbox can be fitted with actuators [182], inertial mass actuators can be used [183] or the drive torque can be used to apply the actuation torque [184]. As additional sensors, actuators and control modules are required, these solutions are mechatronic design elements.

In contrast, self-adaptive solutions do not necessitate these components to enhance the NHV characteristic of gearbox housings. As an example of the elastic mechanism of self-adaptivity, WANG ET AL. [185] and NI ET AL. [186] reduce the vibration and noise level with spring vibration dampers added to marine gearboxes. The FEM and the boundary element method (BEM) were used to investigate the effect of the spring vibration dampers. LIU ET AL. [187] present an effective design process using FEM and BEM to arrange vibration isolation and vibration damping structures on thin-walled planetary gearbox housings. These structures can block the energy transmission path and change the natural mode to avoid resonance frequency. This design process enables engineers to design for the elastic mechanism of self-adaptivity. The challenge is to find the right shape, size and position of the structures. AMARAL ET AL. [179] enhance the NVH characteristics of gearbox housings by introducing vibroacoustic metamaterials while simultaneously reducing the weight by topology optimization. Localy resonant metamaterials (LRM) were applied to the top of the lightweight gearbox housing and experimental results confirmed the effectiveness of the LRM attenuation concept. The authors emphasizes that an early design study identifying the application areas of the LRMs and the main frequency range to attenuate is crucial. HU ET AL. [188] experimentally compare the vibration noise of the gearbox under different cover layers of elastic metamaterials. For this purpose, an optimal unit cell configuration is obtained by topology optimization. Another use of metamaterials for self-adaptive NVH control is presented in LETAIEFF ET AL. [189], where the impact of incorporating a porous material plate into the gearbox housing cover was evaluated through simulation. The addition of a plate with high flow resistivity resulted in a notable reduction in noise generation. An alternative approach is the utilisation of fibre-reinforced polymer composites in the design of gearbox housings. FIGLUS ET AL. [190, 191] investigate composite materials with glass-chopped strand mat, glass fabric, and carbon fabric. Compared to housings made of steel the composite housings are characterized by 60% lower weight and a significant reduction of vibration and noise level above 1 kHz. Gearbox housings made of composite materials, however, show resonant frequencies with higher amplitudes than steel housings in the lower range less than 1 kHz.

In addition to gearbox housings, studies on the design of bearing housings can also be found in the literature. The forces acting on the bearing can only be transmitted securely if the bearing rings are well supported by the surrounding area, for example the housing [192, 193]. The correct design of the elastic housings is therefore crucial for the function of the bearing and the entire powertrain [192]. So-called hard points can lead to undesirably high rolling element loads, while specific compliance can improve load distribution [192]. A positive example is a plummer block housing with an optimized design that leads to a more even load distribution when the housing is deformed and a lifetime that is up to 50% longer [194] (see Fig. 10). Semi-analytical calculation methods [195], FEM [196, 197] and multibody simulations [198, 199] are used to evaluate elastic bearing housings. Although calculation and simulation models for bearing housings are well established, the studies mainly focus on the bearing but not on the impact on the overall system.

In summary, a variety of self-adapting solutions to enhance the NVH characteristic of gearbox housings are subject of research. The principles of self-adaptivity used are limited to elastic [185–187], metamaterial [179, 188, 189] and composite [190, 191] self-adaptivity. Approaches at the microstructure level (material) and the use of kinematic principles are not common and indicate a need for further research. Some studies are purely simulative, other studies include prototypes, but industrial application on a large scale has not yet been realized. A design methodology for the appropriate selection between the self-adapting principles is also missing. The described plummer block housing for bearings is state of the art and is used in various industrial applications. In addition, additively manufactured housings are presented in various works, which aim to reduce casting defects [200], reduce weight [201, 202] or reduce material and energy costs [203] compared to housings manufactured using the classic die-casting process. The impacts on the main functions of the housings are rarely evaluated, so there may be a need for research on self-adaptive mechanisms in combination with additive manufacturing.

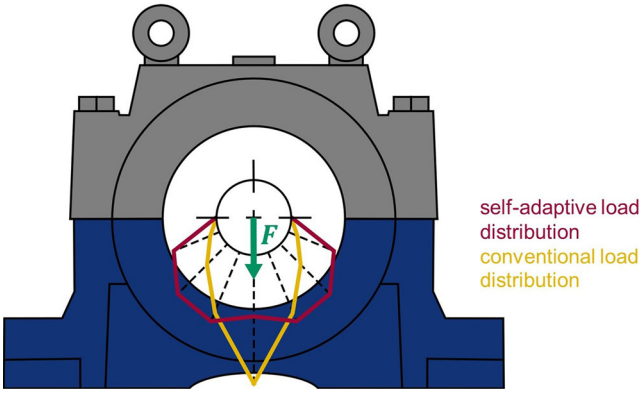


Fig. 10 Adaptive regions of a bearing housing

4.7 Shafts

In machine element theory, shafts are typically built using solid and hollow cylindrical sections, form elements for shaft-hub connections (cf. Sect. 4.3), and mostly standardized undercuts to support manufacturing of the different diameters and functional surfaces. The combination of these different standardized functional sections makes the shaft a design element by definition, as its form does not comply with the typical standards as a whole and serves a specific function [3].

Shafts, as crucial design elements of almost every rotary machine, [204], have the primary mechanical functions of transmitting a usable torque—in contrast to axles—and at the same time taking up functional forces as well as supporting them by bearings (cf. sections 4.1.1 and 4.1.2). In order for shafts to fulfill these functions, they are typically used in combination with power transmitting design elements, such as gears (cf. Sect. 4.8), couplings and clutches and shaft-hub connections (cf. Sect. 4.3).

Despite their widespread use in technical systems, most of the currently conducted research focuses on condition monitoring of shafts, such as SOUFLAS ET AL. [205], who propose a condition monitoring system for transmission shafts based on real-time identification of the physical properties of shafts, such as stiffness or dampening, and their temporal changes. A similar approach, using the shaft itself, its properties and their temporal changes, respectively, for measuring is also proposed by HEINRICH ET AL. [206], where metastable austenitic material sensors are used for fatigue analysis of a shaft. BANSODE & BILLORE [207] provide a comprehensive review on approaches for crack detection in rotary shafts. Currently, new techniques are applied in the field of condition monitoring of shafts, for example, physics-informed neural networks [208] or model-driven machine learning techniques [209] for damage detection.

Although the majority of research conducted in the context of shafts focuses on condition monitoring approaches, little research can be found in the state of research focusing on a targeted adaption of function-relevant properties of shafts, such as their stiffness, for achieving a better functional performance. In this context, WAUER & SUHERMAN [210] proposed an adaptive shaft made from a SMA in order to prevent large resonance deflections in rotor systems. By heating or cooling the shaft by a fixed portion of thermal energy that is provided externally before and after passing the (first) critical speed of a rotor system, the stiffness of the shaft is switched to suppress the transient resonance deflection of the shaft. However, WAUER & SUHERMAN [210] note that—in order to prevent large magnitude vibrations in transient operating conditions—the rotor system, the driving engine and the switching instant must be well-matched, which is oftentimes not possible in practical situations. However, the shaft proposed in [210] does not strictly fit the definition for a self-adaptive design element given in Sect. 1.

In the patent US2016238083 A1, a concept functionally similar to the one proposed by WAUER & SUHERMAN [210] is described by PIORKOWSKI ET AL. [211], see Fig. 11, allowing switching the stiffness of a driveshaft between two defined stages. However, in contrast to the concept described in [210], the driveshaft is not made of a SMA and the stiffness switch does not require externally provided energy and thus a control unit. Hence, this concept of a driveshaft fulfills the definition for a self-adaptive design element given in Sect. 1.

The driveshaft concept described in [211] consists of an inner shaft (1) and a hollow cylinder (2). The hollow cylinder's first end is rotationally fixed to the inner shaft's first end, while the second ends are engaged via a rotational clearance fit. If the torsion of the inner shaft is below a defined limit, the overall driveshaft stiffness is equal to the one of the inner shaft due to the rotational clearance fit between the second ends. However, if the torsion of the inner shaft exceeds the limit due to the transmitted torque, meshing occurs between the not rotationally fixed ends, which increases the overall stiffness of the driveshaft. In order to allow for a gradual transition between these two stiffness stages, a damping element (3) with an internal elastic hysteresis is integrated in between the inner shaft (1) and the hollow cylinder (2).

The crucial point, however, is that any concept for a self-adaptive shaft requires the integration of additional design elements that are essential for self-adaptivity. Although self-adaptivity of shafts has already been described occasionally in the state of research, there is still a lack of tools to be able to use it in a targeted manner in the development of mechanical systems.

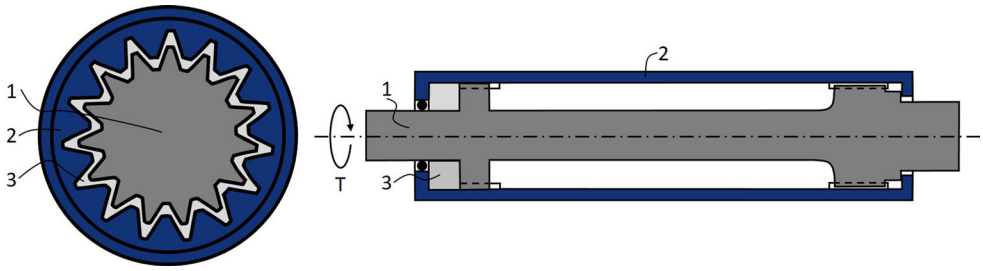


Fig. 11 Concept for a self-adaptive driveshaft (adapted from [211])

4.8 Gears

Gears are common design elements used for power transmission due to their ability to convert speeds and loads torque with a high efficiency and energy density.

A key example for self-adaptive gears is the involute gear, which offers a quasi-adaptive function thanks to their special flank geometry. This geometry enables the gearwheel to adapt to changes in the center distance, which ensures uniform power transmission. In addition, involute gears can be combined with other gears of the same module due to their universal profile geometry, which increases flexibility in the design [212]. Another example of self-adaptive gears are harmonic drives. These typically consist of a flexible gear rim, the flexspline, which adapts to an oval wave generator. The continuous deformation of the flexspline creates a precise and backlash-free transmission with a very high transmission ratio that is ideal for applications with high precision GHORBEL ET AL. [213]. In addition to the properties inherent to the geometry of the gears, HANDSCHUH ET AL. [214] proposed a hybrid gear with a composite material acting as the web of the gear between the gear ring and the metallic hub for the connection to a shaft. This concept was further developed by MASMOUDI ET AL. [215], aiming at decreasing noise and vibration while reduction the weight of the gear (see Fig. 12). They archived a weight reduction of 50% while notably reducing the transmitted vibration in comparison to an identical gear with a metallic gear web.

In the research filed of two-dimensional metamaterials XIN ET AL. [216] have created several metamaterial prototypes using cylindrical gears and planetary gear system to demonstrate their applicability. Based on their arrangement different stiffens gradients can be realized. The gears are for example arranged in quadratic pattern and hold in place by a compliant frame. The gear rim is connected to the hub via two elastic arms with a smoothed variable radial thickness. By designing the thickness of these arms, the properties of the meta cell can be adjusted. Furthermore, ANIK ET AL. [217] have presented an application for metamaterials with gears. They used a metallic gear shape core for a unit cell with a glass-reinforced material base. This cell is a triple-band perfect metamaterial absorber in the terahertz regime. They showed in finite-difference time-domain simulations that the metamaterial with a gear structure can be used to detect glucose, ethanol, oils and cancer cells by changing the resonance frequency and peak absorption of the spectra.

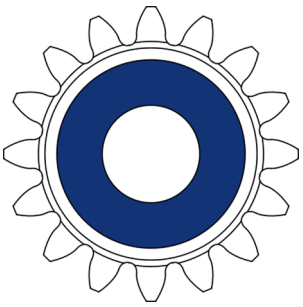


Fig. 12 Concept of a self-adaptive gear with an metal-composite gears body based on [215]

Self-adaptive gears, including involute gears and harmonic drives, provide efficient and flexible power transmission. Innovative designs like hybrid and metamaterial gears enhance performance, offering weight reduction and precise transmission. These advancements demonstrate the potential for diverse applications, from engineering to medical diagnostics.

5 Discussion and summary

The review paper provides an overview of the current state of the art regarding selected self-adaptive design elements. It shows the potential of self-adaptation in enhancing system efficiency and technical availability. Compared to mechatronic design elements, self-adaptive components offer advantages such as reduced complexity and lower energy consumption. Table 2 summarizes the self-adaptive design elements discussed in this review, providing an overview of their improved operating characteristics, stage of development, applied design methodologies, simulation and modeling approaches, underlying principles of self-adaptation, and influencing factors. However, the review also reveals that there is a clear need for further research in areas such as system analysis, design methodologies, material development, and manufacturing processes.

The review highlights that self-adaptivity is present in various applications but at different technology readiness levels (TRLs). Components like springs and seals already

Table 2 Overview of self-adaptive design elements

Design element	Improved operating characteristic	Stage of development	Design methodology	Method for simulation/modeling	Principles of self-adaptation used	Factors influencing self-adaptive behavior
Journal bearings						
Tilting pad bearing [92]	Friction behavior at high speeds (for certain applications (e.g. gas turbines) the tilting pad bearing has completely replaced conventional journal bearings, more stable load-bearing behavior and lower friction at high speeds compared to conventional bearings due to lower bearing clearance)	Established in the industry (widely used for 50+ years)	Design according to [92]; design depending on the Sommerfeld number; tilting pads with bearings allow the bearing clearance to be varied during operation	General behavior can be described by "standardized" formulas, hydrodynamic effects at micro level can only be described by complex CFD	Hinged tilting pads; the oil flows that occur during operation create a balance of forces on the tilting pad and a defined bearing clearance is created (kinematic)	Geometry of the tilting segments, arrangement of the joint, lubricating oil viscosity, shaft speed, load
FlexPad [85, 93]	Concept of a conical journal bearing as the main bearing for drive trains in wind turbines; potentially longer service life than currently used slewing bearings; replacement of individual damaged segments allows reduction of maintenance costs	Prototypes tested and proof of function provided; simulative optimization of macro and micro geometry as well as size scaling	Predominantly simulative design due to high manufacturing and testing costs; initial approaches to multi-criteria optimization	Complex EHD, multibody simulation model for iterative optimization, multicriteria optimization of the topology with regard to load-bearing behavior not yet possible	Flexible structure that allows the segments to be adapted to the displacement of the shaft and thus the uniform absorption of radial and axial forces as well as tilting moments (elastic)	Complex loads due to multi-layered operating modes of the wind turbine and the associated effects on the FlexPad are the state of research, geometry of the tilting segments, stiffness of the material used
Laser textured journal bearings [101, 112]	Reduction of friction due to the formation of microhydrodynamic flows; however, load-bearing behavior is partially negatively influenced	Primarily simulative CFD and EHD investigations; initial experimental investigations carried out	Iterative optimization of the microstructure elements with regard to their geometry, number and position	CFD and EHD simulations, multi-criteria optimization of texturing with regard to load-bearing behavior not yet possible	Development of microhydrodynamic flows through texturization (kinematic)	Geometry, number, position of microstructures
Self lubricating materials [105]	Emergency running properties of the journal bearing in the event of oil supply failure	Self lubricating metal established as a bearing coating material, especially in ship drive trains	Design for steady-state conditions according to DIN 31652 [86]; emergency running properties of materials can mainly be determined experimentally and are strongly dependent on the thermal behavior of the target system, addition of soft metallic materials with a low melting point (e.g. tin)	Mainly through experimental investigations, molecular dynamics as a simulation option for understanding the damage process/melting of the material	Melting of the bearing material at high thermal energy input due to friction, so that a hydrodynamic film of the bearing material is formed and damage to the shaft is prevented (material)	Load, speed, oil viscosity and material properties, in particular melting temperature

Table 2 (Continued)

Design element	Improved operating characteristic	Stage of development	Design methodology	Method for simulation/modeling	Principles of self-adaptation used	Factors influencing self-adaptive behavior
Rolling bearings						
Tube roller bearing [116]	Avoidance of slippage, which prevents lubrication damage when the rolling elements enter the load zone	Prototype tests + pilot applications	Know how, numerical simulation	FEA	Kinematic/Elastic	Force, material properties
Polygonal cage [117]	Regulation of the expansion of the cage, resulting in good guiding properties + low friction in the cage guide at high speeds	Theory (patent specification, commercial use unclear)	Know how, numerical simulation	FEA	Elastic	Rotational speed, temperature, material properties
Gas foil bearings						
Gas foil bearings, gas polymer bearings, conical gas foil bearings [120, 123, 222]	Load capacity, enlargement of the stable operating speed range	Operation in practice or several decades, however, gas polymer bearings and conical gas foil bearings are still under development	Design based on prediction models and prototype testing, different foil geometries, splitting of foils, different polymer material	Very complex multidisciplinary numerical simulations	Elastic, material flexible foil structures and polymer layers ensure sufficient load-bearing capacity for small rotors and largely stable extreme high speed operating behavior thanks to their elastic and damping behavior in combination with fluid-film pressure	Clearances, loading, speed, detailed geometry of bump foils or polymer material properties, wear, coating material properties
Seals						
Shaft seals, O-ring	Compliance with deformations of counter parts	Practice	Know how, numerical simulation	FEA	Elastic, composites	Material properties and shape
Shaft seals	Compliance with shaft misalignment	Practice	Know how, numerical simulation	FEA	Elastic	Material properties and shape
Axial seals (V-rings)	Friction reduction at higher shaft speeds	Practice	Know how, numerical simulation	FEA	Elastic	Material properties and shape
Mechanical seals	Wear resilience	Practice	–	–	Elastic	Material properties and shape

Table 2 (Continued)

Design element	Improved operating characteristic	Stage of development	Design methodology	Method for simulation/modeling	Principles of self-adaptation used	Factors influencing self-adaptive behavior
Floating self-concentric seals [129–132]	Accommodating shaft eccentricity	Practice	Numerical	FEA, CFD	Kinematic	Geometry and operational conditions
SMA as seal energizer [133]	Friction and leakage prevention	Prototype	Trial and error (until now)	–	Metamaterials	Material, geometry and temperature
Couplings						
Couplings [149, 150]	Damping behavior, stiffness	Technology demonstrated in relevant environment	Pneumatic damping elements	–	Kinematic	Air pressure
Couplings [147]	Vibration damping	Technology validated in relevant environment	Via external magnetic field	–	Material	Material combination, external magnetic field
Springs						
Truncated cone spring [163]	Stiffness/Characteristic curve	Practice	Basic design analytical, detailed design FEM	Transfer CAD model or FEM-script-based geometry, elastic or elastic-plastic material, contact, installation context	Change in the effective number of turns during deflection	Acting force or spring travel
Leaf spring (wind turbine blade) [158, 159]	Overload protection and load reduction of wind turbines by reducing the blade angle of attack (= lift) under high wind loads	Experiment	Self-adaptation by adjusting the torsional and bending stiffness of the fiber composite component through targeted asymmetrical fiber orientation	Structure and flow simulation	Coupling of bending/torsion due to asymmetrical stiffness structure of the rotor blades—bending leads to twisting	Wind speed
SMA helical springs [156]	Switching behavior (force/travel), characteristic curve	Practice	Methodology for identifying the relevant material characteristics of the wire is available	FEM, Material model according to Souza-Auricchio [223]	Smart material properties SMA	Temperature
Spring-damper structures with functional materials [160–162]	Dynamic properties (vibration behavior)	Experiment	Methodology for identifying the relevant material characteristics is available	Experimental	Functional material, viscosity reacts depending on the duration of the load/load frequency	Load frequency

Table 2 (Continued)

Design element	Improved operating characteristic	Stage of development	Design methodology	Method for simulation/modeling	Principles of self-adaptation used	Factors influencing self-adaptive behavior
Leaf spring (electr. relay, thermostat) [163, 164]	E.g. overheating protection of electrical devices by interrupting the power supply	Practice	Stacking of two metal strips with different thermal expansion	Calculation of leaf spring deformation depending on thermal expansion	Different thermal expansion of the bimetal switches	Temperature
Flat coil spring [165]	Self-adjusting thermometers, temperature regulators and safety switches, durable and energy-free	Practice	Production of the flat coil spring from bimetal spring strip	Analytical equations of the flat spiral spring and thermo-mechanically coupled finite element models	Various thermal expansion bimetal strips	Temperature
Dampers						
Damper [166]	Attenuation of not just one frequency, but several	Theory	Mass-pendulum damper with variable pendulum length, which changes the natural frequency and thus the frequency to be damped	A genetic algorithm (AI) is used to adjust the parameters of the pendulum, which is modeled as a system with two degrees of freedom, on the basis of loads previously calculated using FEM	Kinematic	Length of the pendulum
Damper [176]	Damping for earthquakes for residential buildings	A prototype was developed	Multiple SMA wires are assembled in series	No simulations carried out	Smart Material	Number of assembled wires, type of SMA
Damper [171]	Ability to dampen vibrations	Prototype	Shaft with permanent magnets at both sides which can slide into a housing with MRF. If that happens, viscosity of the fluid increases and thus friction increases	FEM simulations to calculate magnetic flux density and optimize the design using optimization toolbox in ANSYS	Smart material, Kinematic	Type of used MRF, i.e., material parameters of it
Metamaterials [169, 174]	Vibration damping for a wide frequency range	Numerical and experimental investigation	Specific combination and arrangement of already established structural elements	Analytical, FEM	Metamaterials	Fatique behavior

Table 2 (Continued)

Design element	Improved operating characteristic	Stage of development	Design methodology	Method for simulation/modeling	Principles of self-adaptation used	Factors influencing self-adaptive behavior
Housings						
Bearing housing [194]	Stiffness	Practice	Know how, numerical simulation	Semi-analytical calculation methods, static FEA, multibody simulation	Elastic	Bearing load
Shafts						
Shaft [211]	Stiffness and eigenfrequencies of the overall shaft are self-adapted, Design using conventional design methods for shafts (e.g. DIN 743-1 [224])	Patent (theory), no practical application found in literature	Adaption takes place via the torsion angle of the inner shaft. As soon as the threshold value of the torsion angle is exceeded, the stiffness of the shaft changes to do the "connection" of the hollow cylinder	Conventional FEM-software usable (e.g. ANSYS)	Kinematic	Material and design of inner shaft and hollow cylinder, Material and design of dampening polymer
Gears						
Cylindrical gears [215]	Noise, vibration, harshness and mass	Prototype	Numerical	FEA	Elastic material	Material properties
Taiji gears and planetary gear systems [216]	Continuously tunable elastic properties while preserving stability and shape morphing	Prototype	Numerical	FEA	Metamaterial	Angle and load

exhibiting partial self-adaptivity in their currently standardized, classical forms. However, these designs are relatively simple and primarily rely on elastic principles of self-adaptation. More advanced examples include gas foil bearings, which also use elastic principles to adjust their form based on the load conditions. Beyond these, several self-adaptive concepts exist for sliding bearings, dampers, couplings, and gear systems. The most well-known example is the tilting pad bearing based on the kinematic principle, which has been thoroughly researched and successfully applied in practice for many years. In gear systems, self-adaptive approaches are also known, and some have been successfully implemented in real applications. However, in the case of dampers, most concepts remain at a theoretical or experimental stage. For couplings, there are only a few self-adaptive designs, but those that do exist have already proven effective in practice. Nevertheless, a variety of promising concepts—such as self-adaptive shafts and housings—remains underdeveloped. For the concepts presented so far, typically only one or a limited set of self-adaptive principles—such as elastic or kinematic—have been exploited. In reality, a broader combination of principles could be employed to fully harness the potential of self-adaptivity. It is documented in the literature that, for example, metamaterials are designed as composite materials [20, 57] and compliant mechanisms are developed from metamaterials [52]. Yet, such integrated approaches remain largely underexplored in self-adaptive design elements. This gaps are particularly striking, considering the potential benefits of self-adaptive design elements. The question arises: Why haven't self-adaptive design elements gained widespread adoption despite their clear advantages, apart from specialized applications like gas foil bearings or seals?

To understand why many self-adaptive concepts have not yet achieved widespread implementation, it is crucial to first quantify their potential. This requires robust simulation and analysis methods capable of accurately modeling the impact of self-adaptation on system behavior, typically through the development of multiphysical models. Modeling aims to create mathematical and descriptive substitution models of the system or its subsystems that describe the structure and behavior with sufficient accuracy [13]. Although modern modeling techniques are generally well-suited for a wide range of scenarios, they often need to be tailored to specific applications, requiring significant expertise and domain-specific knowledge. One of the main challenges lies in the high computational effort, especially when addressing dynamic effects. This becomes particularly demanding when the simulation must be conducted within an optimization to determine the optimal self-adaptive behavior. To manage this efficiently, fast and reliable surrogate models are essential for balancing computational speed and accuracy while ensuring robust results.

A further complication stems from the uncertainty of operating conditions. Boundary conditions for these models are often not clearly defined, leading to ambiguity regarding the full range of scenarios the system may encounter. Without this clarity, predicting the performance and robustness of self-adaptive systems becomes a major obstacle.

Even when the manner in which a design element should respond to changing operating conditions is conceptually evident, the effective realization of an appropriate adaptation mechanism remains a substantial challenge. To date, the development of self-adaptive mechanisms continues to rely predominantly on conventional engineering practice and expert knowledge, as structured design methodologies capable of systematically translating desired adaptive effects into technically feasible solutions are still lacking. In particular, no design-oriented framework currently exists that consistently links adaptive objectives, underlying operating principles, and their constructive embodiment. Although generally applicable design principles for self-adaptive design elements can, in principle, be derived, these have not yet been systematically formulated, differentiated, or integrated into engineering design methodology in the sense of established design frameworks such as Ref. [218]. At the same time, it must be recognized that self-adaptive design is inherently multidimensional and therefore cannot be adequately captured by a single universal design approach.

Current design implementations typically focus on a narrow range of adaptation principles, with materials, elastic and kinematic principles being the most common, while other potentially beneficial approaches remain underutilized. This limitation, combined with the lack of comprehensive design guidelines or design tools, often forces designers to rely on trial-and-error processes. Although adaptation can enhance specific performance characteristics, it may also degrade others, leading to complex trade-offs. For example, in sliding bearings, locally reduced stiffness can improve operational efficiency but may conflict with the need for overall structural stiffness. This underscores the importance of a comprehensive approach to system integration, where the interactions between subsystems are carefully evaluated. Multicriteria optimization presents a promising solution to address such challenges by simultaneously evaluating multiple design objectives. However, it is still underutilized. In sliding bearings, for instance, optimization should consider hydrodynamic performance under varying conditions, local stiffness, temperature-dependent deformations, and global structural stability. The unique criteria for each design element further complicate the creation of a universal design methodology. Even small increases in structural complexity can significantly amplify the challenges of modeling and design, as additional interactions and dependencies must be accounted for. As a result, developing accurate and efficient models becomes

increasingly demanding. Emerging tools, such large-scale optimization and artificial intelligence (AI), offer new possibilities for managing the complexity of multidimensional design problems. Certain factors, however, remain challenging to address directly during the design phase. Long-term material fatigue and complex boundary conditions in real-world applications often cannot be fully captured through simulations alone. Therefore, extensive practical testing is crucial for generating data to refine designs and evaluate interactions. These experimental insights play a vital role in closing the gap between theoretical optimization and real-world performance. Moreover, integrating self-adaptive mechanisms into compact, space-constrained designs presents additional challenges. Designs must not only satisfy functional requirements but also adhere to packaging constraints, increasing development complexity and costs. Consequently, the design of self-adaptive elements is resource-intensive and requires longer development times compared to conventional components.

Additive manufacturing offers considerable potential for the development of self-adaptive design elements, as it enables the realization of complex, highly integrated structures that are difficult to manufacture using conventional processes [219, 220]. In particular, monolithic structures with locally tailored mechanical properties can be fabricated, which supports the implementation of integrated self-adaptive design elements. In addition, additive manufacturing facilitates rapid prototyping and iterative development, which is especially beneficial given the high development effort and long development cycles associated with self-adaptive design elements [219]. At the same time, limitations in material performance, process robustness, production speed, mechanical properties, and costs currently constrain the wider industrial application of additive manufacturing [221], indicating that further research is needed to fully exploit the potential of additive manufacturing in this context.

However, self-adaptive elements in general offer significant potential to address key challenges such as resource efficiency, sustainability, and energy optimization, making further research and development highly worthwhile.

6 Open challenges and potential directions for future research

While self-adaptive design elements offer great potential, several challenges remain that need to be addressed. To advance their development, future research should focus on the following key areas:

- Lack of self-adaptive designs for special groups of design elements: Most existing approaches focus on design elements like seals and springs, while design elements such as shafts and housings remain underexplored, despite their potential to enhance system performance and adaptability.
- Limited integration of self-adaptive principles: Current designs often focus on a single self-adaptive principle, leaving the potential benefits of combining multiple self-adaptive principles underutilized. Exploring their integration could enhance overall system performance and resilience.
- Need for automated design processes and performance trade-off management: Many self-adaptive design elements are still developed manually, with limited use of computational design and optimization techniques. Implementing multi-objective optimization methods tailored to specific design element groups could help balance performance trade-offs, ensuring that improvements in certain aspects do not come at the expense of others, while also reducing development time.
- The need for efficient modeling: The complexity of designing and validating self-adaptive design elements results in long development cycles. Implementing surrogate models can reduce computational effort and accelerate the design process.
- Uncertain operating conditions insufficiently integrated into models: Current theoretical models often fail to account for the variability and unpredictability of real-world environments. Addressing this gap could enhance design robustness.
- Need for experimental validation and lifecycle considerations: Many self-adaptive design elements remain theoretical or exist only as prototypes, lacking comprehensive real-world testing. Long-term experiments under practical conditions are essential to assess durability, feasibility, and operational reliability, as their behavior cannot always be fully predicted in advance. Additionally, design approaches should incorporate full lifecycle considerations from the outset.
- Holistic system-level perspective: Future designs should consider entire systems rather than isolated components, accounting for interactions between subsystems and the effects of self-adaptation on overall system behavior.
- Need for general design guidelines: Development of general design rules, similar to those that exist for classical machine elements.

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Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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