Constant Torque Mechanisms: A Survey

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This work gives an overview of all types of constant torque mechanisms (CTMs) based on both function and structure. Based on their architecture they can be divided into five distinct categories which all have their specific behaviour. It is also shown that these CTMs can be divided into two application types, namely power assistance or torque stabilisation. Constant force mechanisms (CFMs) are more prevalent in the literature, therefore, some discussion is proposed on how CFMs can be transformed into CTMs. It is also shown that some of these CTMs have a very high specific energy which makes them potentially interesting for use as energy storage/power providers in novel fields like robotics.

Nomenclature
CTM Constant Torque Mechanism.
CFM Constant Force Mechanism.
T Torque.
θ Deflection.

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1 INTRODUCTION

For actuators, each specific task is characterised by a certain torque-rotation or force-displacement profile. Performing this task can either be done using stiff actuators, i.e., when (a) motor(s) is directly coupled to the output, or by compliant actuators, i.e., when a compliant element or mechanism is placed between the motors and the output. The advantages of placing springs in the system is to decouple the inertia from the in- and output such that the transmission is protected from impacts coming from the output side [1] and to reduce the energy losses since a part of the energy can be delivered by the compliant element [2–5].

There are four basic profiles of compliant mechanisms that can be observed in literature, which are depicted in Fig. 1, more complex behaviour can be achieved by combining the basic shapes. These profiles can be categorised by their stiffness k ($= \frac{dT}{d\theta} = \frac{dF}{dL}$), i.e., the slope of the curves shown in Fig. 1. The most basic relationship is the linear relation where k is a non-zero constant. Examples of these are most common springs like compression and tension springs (for $F = k\Delta L$) and spiral and torsion springs (for $T = k\Delta\theta$). The remaining compliant mechanism profiles are, on the other hand, nonlinear. From Fig. 1, profiles 1 and 3 are both influenced in a non-linear way by the deflection, which is a behaviour that is sometimes seen for spiral springs [6]. In the case of profile 1 the stiffness of the mechanism becomes lower as the deflection increases. Due to this behaviour, it is called a softening or degressive mechanism. In the case of profile 3 the stiffness increases as the deflection increases, which is why such mechanisms are called stiffening or progressive mechanisms [7]. This stiffening behaviour is for example used in legged robots [8].

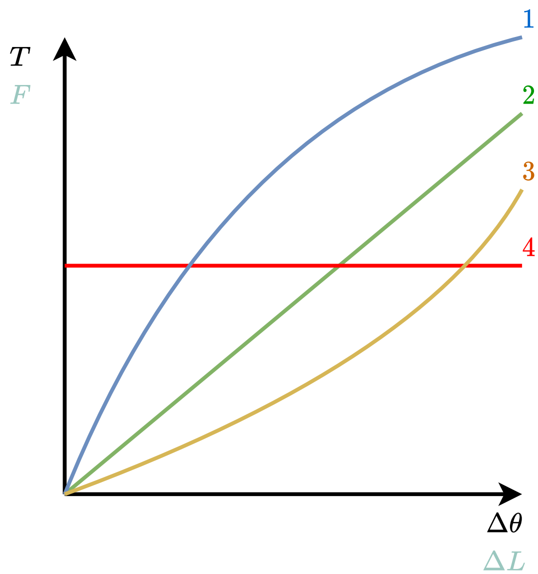


Figure 1: Typical force-torque/deflection profiles of compliant elements. Here the blue curve (1) represents non-linear softening behaviour, the green curve (2) a linear behaviour, the yellow curve (3) a non-linear stiffening behaviour and the red curve (4) represents a constant force/torque behaviour.

The last of the basic profiles, i.e., profile 4, distinguishes itself by its stiffness $k = 0$, which results in a so-called constant force or constant torque mechanism (depending on whether we look at a linear or an angular motion). This kind of behaviour is needed in applications where the force or torque has to be regulated at a fixed level, invariant of the driving speed or deflection/rotation. Usually when this feature would be needed, active compliance would be applied and hence extra sensors would be necessary in order to track changes in force/torque and deflection/rotation. This leads to an increase in size, cost and complexity of the control architecture and overall energy consumption due to all the extra sensors [9].

Hence, by introducing a passive compliant mechanism which achieves the same desired functional characteristics, i.e., a constant force/torque profile, complex control structures and integration of numerous sensors can be avoided. When drawing a parallel to the field of robotics, the force-curve, i.e. F vs. ΔL, is related to the behaviour of prismatic joints, whereas the torque-curve , i.e. T vs. $\Delta\theta$, relates to the behaviour of revolute joints.

This work focuses on the mechanisms that can perform the constant profile, since these have not yet been as thoroughly examined as their constant force counterparts. The kind of structures related to this behaviour is called Constant Torque Mechanism (CTM).

1.1 Functional classification

CTMs have many different applications, which can be categorised according to their purpose, i.e., *Power Assistance* or *Torque Stabilization*. This division can be seen in Table 1, where examples of different applications are listed according to their respective category.

Torque Stabilisation	**Power Assistance**	
Timing Device	Deploy Mechanism	Mobility Support
Drawing/Extrusion Mechanism	Rehabilitation Device	Elastic Motors
	Reeling System	

Table 1: Overview of the different types of applications that use constant torque actuation together with the classification of the areas in which they fall. CTMs can be either applied for Power Assistance purposes or for Torque Stabilisation.

Power Assistance CTMs are meant to perform a task autonomously or reduce the effort to do it.

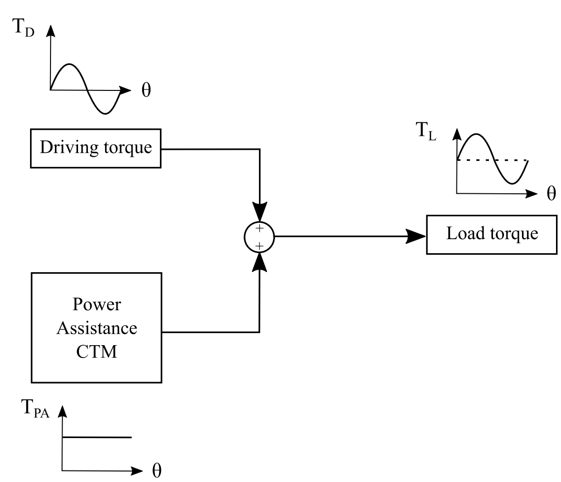


Figure 2: Graphical representation of the principle of Power Assistance CTMs. Here it can be seen that the torque of the input motor (T_D) can be reduced since the Power Assistance CTM (T_{PA}) partially helps to provide the necessary load torque (T_L).

This working principle is displayed in Fig. 2, but it can also be intuitively explained by looking at everyday objects like a measuring tape or a seat belt. In the case of a seat belt, for automatic retraction, a spring needs to be added to the system. However, if the spring is linear, the torque exerted by the passenger to put the belt in the locker would increase constantly. Since this is, of course, not the desired behaviour, a constant torque retracting mechanism is used. This mechanism allows fastening the belt, i.e., stretch it, without experiencing a change in the necessary torque throughout the entire working range. Upon release, the mechanism still retracts the belt into its initial position like any other spring would do.

The Power Assistance Mechanisms can provide their power in one or both angular directions. An example of a one-way mechanism is a *Deploy mechanism*, like e.g., in aerospace appendages [10–12] where the constant torque mechanism, usually a constant torque spring, provides the energy to deploy the solar panels of a satellite. This one-way assistance can also be found in reeling systems, like e.g., in fishing lines, automotive hoods, dog leashes, measuring tape or seat belts, and in several winding toys where a constant torque mechanism, usually a specially tied rubber band or small constant torque spring, is used as an elastic motor to drive the toy [13–15].

When looking at CTMs that provide power assistance in both angular directions, one can note that a lot of devices are applied for motion assistance (*Mobility Support* or *Rehabilitation devices*). This assistance can be either continuous or temporary.

When the assistance is only temporary, e.g., for rehabilitation, constant torque mechanisms are often used, since muscle stretching under constant torque improves and accelerates the recovery process in comparison to other stretching methods (e.g., with torque that increases when the muscles are stretched further, which happens when linear springs or mechanisms are used). This can ease the recovery process, e.g., for patients who suffered from a stroke [16, 17].

These findings have already resulted in several dynamic splints, braces and orthoses [18, 19] which allow to perform the necessary muscle stretching needed to attain full flexion again after injuries, strokes or operations.

In the case of *Mobility Support*, i.e., where the power assistance is continuous, the main motivation to use a CTM is to reduce the torque-requirements of the task that needs to be performed [20–23]. Another motivation for the use of CTMs is a principle that will be named *'Zero Torque Shift'* in this paper.

The principle of Zero Torque Shift, which is illustrated in Fig. 3, allows to offset the torque profile of a given task such that the maximum torque in both directions is equal. One could say that this Zero Torque Shift balances out the torque profile that has to be performed.

The Zero Torque Shift principle is used in, e.g., exoskeletons such that the motor size can be reduced [21, 22]. This reduction in size becomes possible since the maximum torque in both directions is balanced and hence the motor choice is no longer dependent on the torque in one direction. A practical example of an unbalanced load profile is e.g. the gait cycle of an ankle joint where the maximum torque in one direction is approximately 120Nm, whereas it is approximately 0.5 Nm in the other direction for someone with a weight of 75kg [24].

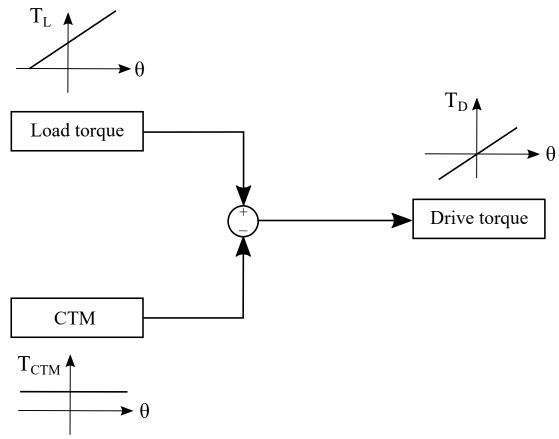


Figure 3: Visual representation of the principle of *Zero Torque Shift*. Here the asymmetric load (T_D) will be compensated by a constant torque input (T_{CTM}) such that the driving motor has to deliver a symmetric torque profile (T_L), i.e., the maximum torque in both directions is equal. This allows to scale down motors.

Torque Stabilisation CTMs, on the other hand, describe all systems which have the function of stabilising any torque ripple that might occur in the process in which the mechanism is implemented. Torque stabilisation is visualised in Fig. 4.

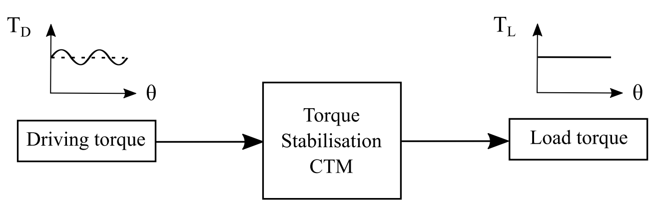


Figure 4: Graphical representation of the principle of torque stabilisation CTMs. Here the ripple on the driving torque (T_D) will be stabilised by the CTM such that the load torque (T_L) becomes ripple free.

These Torque Stabilisation CTMs only work in one direction. An example of these are *Timing devices*, in which torque ripple is a problem that can influence the periodicity of the system they need to control. A change in the periodicity (time management) is, however, an unwanted characteristic for applications like, e.g., clocks and fuses for bombs, since there a precise time regulation is crucial. This explains why many CTMs have been developed in order to tackle the problem of timing devices in which the periodicity becomes longer and longer (mechanism starts to become slower) [14, 25, 26].

Another example of applications that require a stabilised torque input is *Drawing/extrusion applications*. These comprise processes like yarn pulling for weaving machines, rewinding mechanisms for record sheet (e.g. journals), metal pulling/rolling to regulate the thickness, etc. [27–29]. In those applications a constant torque is crucial since fluctuations on the speed might occur. However, it should not result in fluctuations on the torque, since that might induce unwanted characteristics (e.g. different thickness of a metal plate) or even failure of the materials handled by the CTMs.

1.2 Structural classification and lay-out of the paper

Aside from categorising the different types of constant torque mechanisms according to their function or application, they can also be classified based on their structural characteristics. When a constant torque needs to be achieved through a compliant mechanism, the following equality needs to be met:

$$\frac{dT}{d\theta} = 0 \tag{1}$$

Where T represents the torque and θ the output deflection. However, this equation does not specify how the constant torque can be achieved. Hence, the above equation can be rewritten as:

$$\frac{dT}{dQ_{spr}} \cdot \frac{dQ_{spr}}{dQ_{mech}} \cdot \frac{dQ_{mech}}{d\theta} = 0 \tag{2}$$

Here, Q_{spr} represents the deflection of the compliant element and Q_{mech} the input of the mechanism attached to the compliant element. From this expression it can be deduced that a constant torque can be obtained by:

1. Shaping the characteristics of the compliant element ($\frac{dT}{dQ_{spr}}$).
2. Shaping the influence of the compliant element on the deflection of the mechanism it is coupled to ($\frac{dQ_{spr}}{dQ_{mech}}$).
3. Shape the transmission ratio between the real output and the output of the mechanism ($\frac{dQ_{mech}}{d\theta}$), e.g., gearboxes and four-bar linkages.
4. Shape a combination of the previous possibilities.

Taking this remark into account, one can distinguish five different categories of constant torque mechanisms, which are all shown in Fig. 5.

Among the five categories, two are pure joint mechanisms, i.e., the input- and output axis are aligned. When looking at the joint mechanisms, both categories can be divided based on the properties of their structure. If the entire structure is made of flexible material, i.e., elastic materials, they fall under the category of *'Distributed Compliance Mechanisms'*. However, if the structure is composed of both flexible and rigid elements, they fall under the category of *'Lumped Compliance Mechanisms'*.

Both categories can also be further divided into three subcategories. For the distributed compliance mechanisms, the division is made according to the type and behaviour of the beams used to connect the input- and output shaft. Those can either be *Curved Beams*, *Pre-compressed Beams* or *Bistable Beams*. For the lumped compliance, the division was already made in [30], based on their principle to obtain zero stiffness for the overall mechanism. However, the authors only mentioned the type of mechanism: type A, B, or C). In this work, they will be referred to as *'Stiffness-combination Mechanisms'*, *'Cam-based Mechanisms'* or *'Friction-based Mechanisms'*, respectively. A more in-depth explanation of the lumped compliance mechanisms will be given in section 2, whereas the distributed compliance mechanisms will be tackled in depth in section 3.

When talking about the parallel axis mechanisms there are three subdivisions, namely *'C-shaped Spring Mechanisms'*, *'Elastic Deformation mechanisms'* and *'Constant Force-based mechanisms'*.

The *C-shaped spring mechanisms*, which will be treated in section 4 are the most common way used in the industry to achieve constant torque, since they are made by spring manufacturers at predefined torque rates and can easily be integrated in a specific design. *Elastic deformation mechanisms*, on the other hand, which will be investigated in section 5, are usually made out of polymer materials that possess rather high strain properties and are mainly used for toys as a sort of mechanical battery. In section 6, the *Constant Force-based Mechanisms* will be discussed. Here a closer look will be given at the different kinds of constant force mechanisms that can easily be transformed into constant torque mechanisms.

Finally, a comparison among all types will be given in section 7 based on different parameters like deflection range, cost, ability to maintain a constant torque, etc. This is followed by a final discussion, together with a short reflection of the authors on current research about Constant Torque Mechanisms and which open challenges remain to explore in the future for the field in general. This last part is provided in section 8.

2 Lumped Compliance

When talking about lumped compliance, all the mechanisms that work based on the deformation of some distinct integrated flexible parts, e.g., springs, will be considered. It is assumed that the rest of the mechanism behaves as a rigid part whose function is either guidance, structural stability or connection.

These lumped compliance constant torque mechanisms

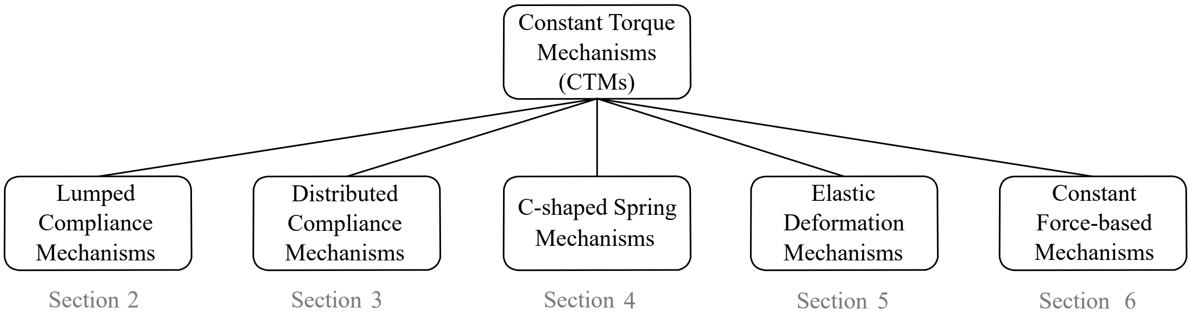


Figure 5: Classification of the different general types of constant torque mechanisms.

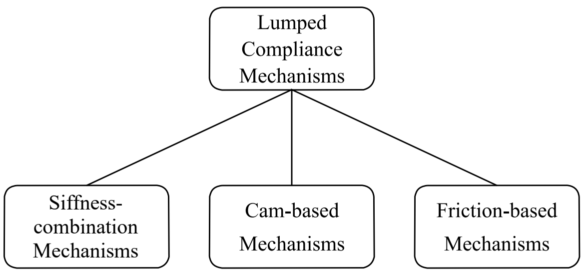


Figure 6: Classification of the different types of Lumped Compliance CTMs.

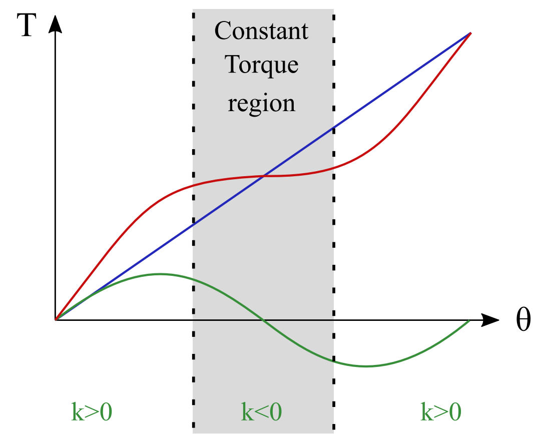


Figure 7: Representation of the working principle of a Stiffnesscombination Constant Torque Mechanism (CTM). In this figure, the blue curve represents the spring with a positive stiffness. The green curve represents the spring which changes the sign of its stiffness due to the mechanism construction. It has three regions, a positive stiffness range ($k > 0$), a negative stiffness ($k < 0$) and again a positive stiffness. In the $k < 0$ region, the second spring negates the one of the blue curve which makes that the CTM, represented by the red curve, shows a constant torque region (grey area).

can, as shown in Fig. 6, be divided into three categories, namely *Stiffness-combination Mechanisms*, *Cam-based Mechanisms* and *Friction-based Mechanisms*, which will be discussed in detail in the following section.

2.1 Stiffness-combination Mechanisms

The CTMs of this group are given the name *Stiffness-combination Mechanisms* since they combine different elastic elements, where at least one elastic element is showcasing a positive stiffness and at least one negative stiffness. By combining these, a quasi-zero stiffness and hence a constant torque output is generated. This behaviour is shown in Fig. 7 where the blue and green curves represent the behaviour of the separate elastic elements (springs) and the red curve represents the behaviour of the entire mechanism. In Fig. 7, one can notice the region providing constant torque.

In Fig. 8, examples of this type of mechanism are shown. Figs. 8 (a)-(c) display mechanisms where the negative stiffness is produced by linear springs (compression/tension). These linear springs build up force and hence torque for a positive rotation until they are at their maximally compressed state. Afterwards, the mechanism starts pulling the spring while there is still a positive rotation, which will result in a negative stiffness region. The positive stiffness, on the other hand, is produced by torsional springs. In Fig. 8(d), the mechanism is built with a combination of torsional springs, where the inner one still produces positive stiffness, and the springs connected to the bars produce negative stiffness.

Due to the fact that some elements are fixed, the rotational range of this type of mechanism is limited and hence the placement and size of each part should be evaluated.

2.2 Cam-based Mechanisms

The CTMs of this group are given the name *Cam-based Mechanisms*, since they use a cam profile to create a zone of invariance in the working range of the mechanism, such that the torque does not change in function of the deflection in that specific zone. Like this, a constant torque curve can be created as shown in Fig. 9.

This construction can be achieved in various ways as demonstrated in Fig. 10.

From all the configurations represented in Fig. 10, the one labelled (c) has the highest range of constant torque for a certain size, since it wastes the least of space to fully stretch its spring. In [31] it was shown that this type of mechanism can reach a range of 270°. However, they use a rather weak spring. By choosing an optimal spring, based on the catalog values [32, 33], and combining it with the formula derived

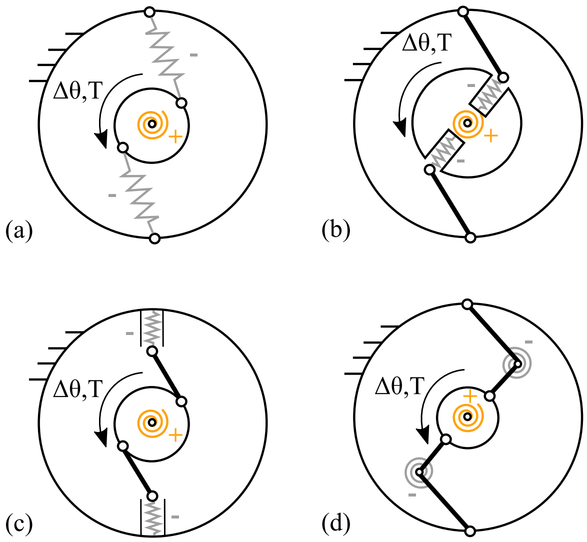


Figure 8: Graphical representation of the different ways a Stiffness-combination Mechanism can be made to design a Constant Torque Mechanism (CTM). Here, the orange parts represent the springs that have a positive stiffness and the grey parts represent the spring which shows negative stiffness properties. Figure adapted from [30] with permission from Elsevier.

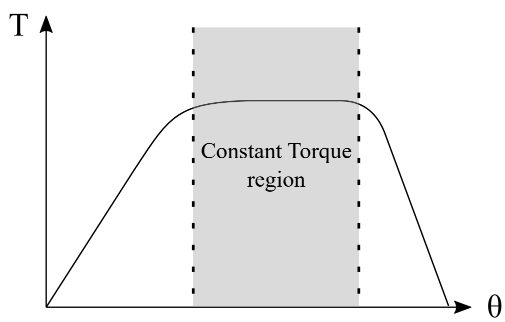


Figure 9: Representation of the output characteristics of a Cam-based Constant Torque Mechanism (CTM). In this figure it can be seen that there is a region, indicated in grey, where a further rotation of the output does not produce a different torque. This is due to the fact that the cam, where the spring is attached to, creates a zone of invariance. This zone is the constant torque region.

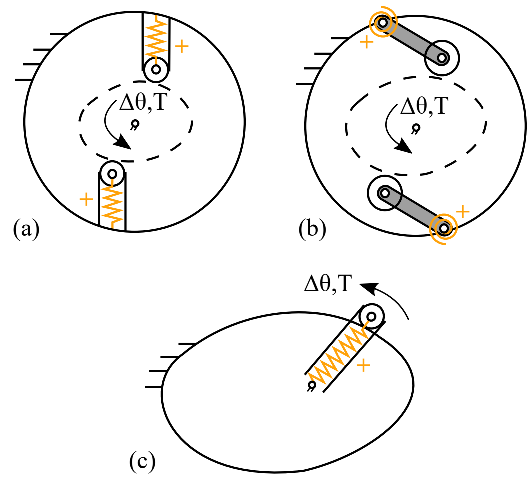


Figure 10: Graphical representation of the different ways a Cam-based Mechanism can be made to result in a Constant Torque Mechanism (CTM). Figure adapted from [30] and [31] with permission from Elsevier.

in [31], torque of up to $4-5Nm$ can be obtained when the radius of the cam is $5cm$. If this radius is increased until $10cm$, this torque range can even reach $20-25Nm$ according to calculations.

2.3 Friction-based Mechanisms

The last group of Lumped Compliance CTMs is given the name *Friction-based Mechanisms*, since they rely on a steady friction force to set the desired torque level. If that torque level is not reached as input, the mechanism will not move. If, however, the desired torque level is reached, still only the target level will be transferred to the output, since a mechanism is usually built in to allow relative motion to compensate for the possible excess torque. The only requirement they have is that the friction force needs to be sufficiently stable, which can be achieved by various means, e.g., magnets, friction seals and plates, gearings, preset springs, etc. [25–28, 34–37].

The fact that these mechanisms are friction-based results in a rotational range which is in fact unlimited, since the friction mechanism turns together with the output if the necessary input torque is reached. The torque level, on the other hand, is limited by the friction force and is also scalable to rather large ranges. This results in a steady constant torque over the entire range as shown in Fig. 11, which gives a higher range than the other Lumped Compliance systems.

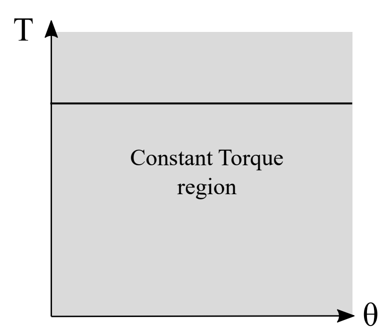


Figure 11: Representation of the output characteristics of a Friction-based Constant Torque Mechanism (CTM). In this figure it can be seen that the entire region provides constant torque (indicated in grey). This is due to the fact that the friction mechanism only allows motion when the necessary torque is reached. Afterwards there is no limitation on the possible deflection range.

These mechanisms are, however, also constructed in such a way that they will never deliver torque, but only stabilise it, which is why it is the most used mechanism for *torque stabilisation* purposes. These mechanisms can be found in applications like e.g. winding machines [27–29].

The construction of these mechanisms can be achieved in various ways as demonstrated in Fig. 12. There, Fig. 12 (a) represents the mechanisms where a pushing element (in orange), attached to the inner shaft, applies a pressure on the friction element (in grey) such that a constant friction torque is generated between the friction element and the stationary outer ring. Fig. 12 (b), on the other hand, represents the systems where a pushing element, attached to the stationary outer ring, applies a pressure on the friction element such that a constant friction torque is generated between the friction element and the inner shaft. The element that needs to generate a stable friction force (in grey) can be a lot of different things, e.g., friction plates or gears, as mentioned before.

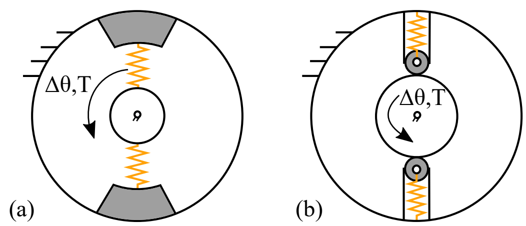


Figure 12: Graphical representation of the different conceptual ways a friction based mechanism can be made to design a constant torque mechanism (CTM). Here, the part in orange represents the pushing element that applies a pressure on the element that generates the stable friction (in grey). Figure adapted from [30] with permission from Elsevier.

2.4 Conclusion

Regarding the rotational range, Lumped Compliance Mechanisms exhibit in general a range large enough for a lot of applications. Among those the Stiffness-combination Mechanisms have the smallest range, which is limited until approximately a half turn. However, for the Cam-based Mechanisms, this goes up to $3/4$ of a turn. The Friction-based Mechanisms, on the other hand, have by far the largest rotational range, since it is unlimited.

Regarding the torque level, the Stiffness-combination Mechanisms perform again the poorest, due to the fact that there is not a very high rotational range to build up torque and because the negative stiffness spring does not have a very high slope (necessary to build up torque) due to the intrinsic post-buckling behaviour. Cam-based Mechanisms are not only limited by their spring, but also by the radius of the cam. If the cam is bigger it inherently means that the produced torque increases, however, the range of applications in which it can be implemented is reduced. In robotics one can say that a cam radius of $5cm$ is already rather large, which results in torques up to $4-5Nm$, which is already significant, but this can be increased drastically if the outer radius of the cam is increased (e.g., up to $20-25Nm$ for a doubled radius). For the last category of Friction-based Mechanisms, the torque is limited by the friction force that can be produced in the system. This is, however, less of a problem since that category of mechanisms is only applicable for torque limiting purposes. The Stiffness-combination and Cam-based Mechanisms are, on the other hand, only used for Power Assistance.

3 Distributed Compliance

When talking about distributed compliance, the mechanisms working based on the deformation of their entire structure (not only from individual parts) will be considered. These compliant mechanisms exploit the bending of their flexible members to achieve the motion and force/torque [38, 39] and hence can be seen as a type of constant torque mechanism that achieve constant torque entirely by playing with the characteristics of the spring.

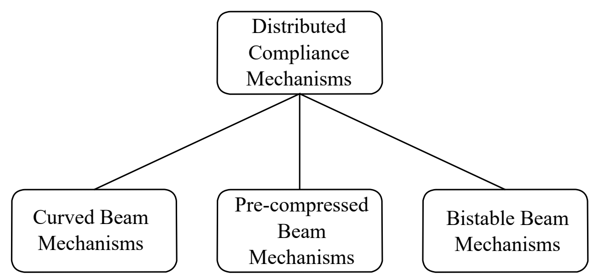


Figure 13: Classification of the different types of Distributed Compliance CTMs.

These Distributed Compliance Mechanisms can be divided into three distinct types based on how the flexible members, that connect input and output, are designed. One can distinguish *Curved Beam CTMs*, *Pre-compressed Beam CTMs* and *Bistable Beam CTMs*, which are shown in Fig. 13. Those are discussed in more detail in the following section.

3.1 Curved Beam Mechanisms

Constant Torque Mechanisms based on compliant elements take, as mentioned, advantage of the fact that their elastic or recoverable deformation generates a certain force/torque. It is, however, not possible to immediately attain a constant, non-zero torque level, since that would impose a torque at zero deflection, which is impossible due to the fact that there is not yet a reaction force/torque that can be generated without movement. Hence, a realistic curve imposes that the constant torque level is reached after a rotation θ_{pre}, as shown in Fig. 14. The rotational range needed to achieve the constant torque level is called the pre-loading range.

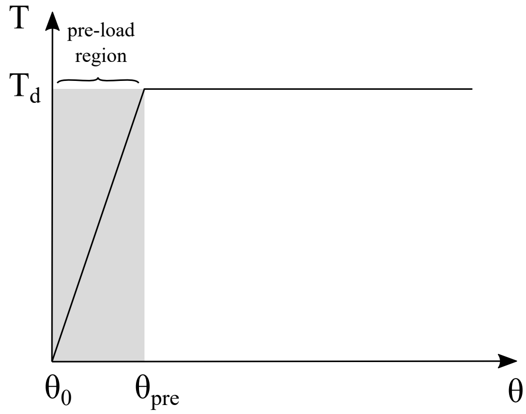
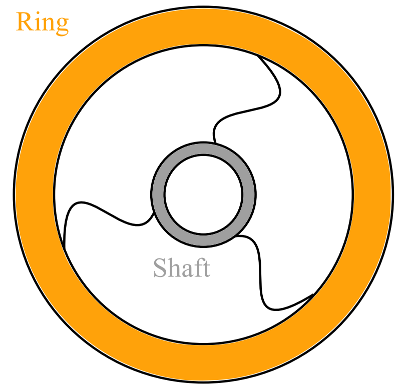


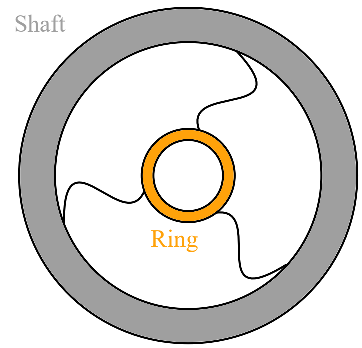
Figure 14: Representation of a realistic $T-\theta$ curve for a compliant Constant Torque Mechanism. Here, T_d represents the desired torque level and θ_{pre} the deflection that the CTM has to undergo to reach that desired torque. The region up to θ_{pre} is indicated in grey and represents the (non-useful) pre-load region.

In order to follow this $T-\theta$ profile, a set of compliant (curved) beams needs to be designed such that their reaction torque at deformed state follows the desired profile with minimal deviation. These curved beams are placed inside an annular design that has an inner and an outer ring connecting the end-points of the beams. From both rings, one ring is always fixed and the other is the rotation shaft. Both possible arrangements are shown in Fig. 15.

The parameters involved in the construction of these curved beams have to be optimised in order to form a curve that can produce the desired $T-\theta$ profile with minimal deviation.



(a) Compliant annular design with fixed outer ring.



(b) Compliant annular design with fixed inner ring.

Figure 15: Representation of the two possible compliant annular designs. Here, the orange ring represents the fixed ring and the grey one the rotation shaft. Both rings are connected by the curved beams.

3.2 Design choices and implications

To produce the torque profile shown in Fig. 14, there are several boundary conditions that need to be taken into account, e.g., desired torque, pre-loading range, maximum allowable stress, etc. In the following subsection, an overview will be given of the possible choices that can be made and how they affect the overall performance of the created compliant CTM.

3.2.1 Curve fitting

One of the first choices that has to be made during the design phase is the type of curve fitting method that is going to be used. In short, one can say that the chosen curve fitting method decides how the data points, which are generated through the optimisation process, affect the final design of the parametric curve.

There are two distinct curve fitting methods, namely

- Approximation fitting
- Interpolation fitting.

For the approximation fitting method, the parametric curve is drawn towards the generated set of data points, but does not require to pass through the exact location of these points, which are called control points if the approximation method is applied [40].

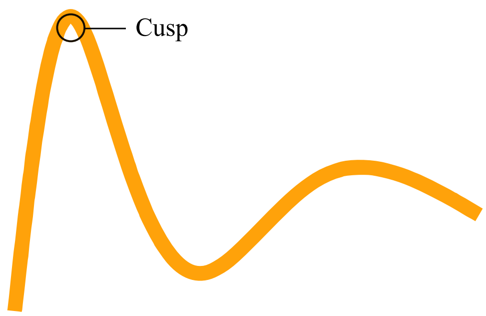
For the interpolation fitting method, on the other hand, the parametric curve needs to pass exactly through the generated set of data points, which are called interpolation points if the interpolation method is applied [41]. Usually the interpolation method is applied, since this provides results which are closer to the initial requirements.

3.2.2 Type of curve

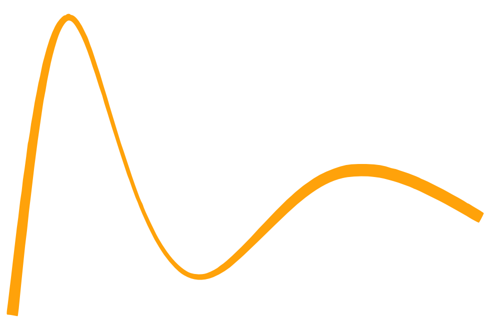
When developing the parametric curve into the curved beam, which is going to be used in the constant torque mechanism, an important parameter to look at in the optimisation process is the stress level in the curved beam. This stress is highly dependent on the used beam width of the derived spline. One can distinguish two types of curves based on their beam width, namely

- Uniform width spline.
- Variable width spline.

For a uniform width spline, the optimisation program will loop over different widths and adapt its entire design to the smallest width that gives results where the stress inside the material will not be fatal. While doing this, care should be taken for the stress concentrations that appear when a certain area of the curve is not smooth enough. According to the wide curve theory, "a curve is not smooth when its uniform width is above its critical value, which is twice the minimum radius of curvature of the centre spline curve" [42]. This phenomenon, which is demonstrated in Fig. 16 (a), is called *'cusp'* and should be avoided to prevent premature failure. This can be done by allowing the width to change throughout the curve and by adding the boundary condition in the optimisation process that the width of the derived beam curve should never exceed its critical value.



(a) Uniform width cubic spline curve with cusp.



(b) Variable width cubic spline curve without cusp.

Figure 16: Representation of the cusp phenomenon and how this can be avoided by changing locally the width such that there is no longer a critical point. Figure adapted from [43] with permission from ASME.

This can, however, lead to conflicting demands, since sometimes, the width needs to be increased to avoid excessive stress in the beams, whereas in other cases the width has to be reduced in order to comply to the cusp-restriction. Therefore, a variable width spline can better be used, as depicted in Fig 16 (b)).

To determine the shape and size of this spline, interpolation circles may be used. As shown in Fig. 17, each interpolation circle is described by the radial distance, r, from its center to the center of the annular region, the angle, β, between a reference axis and the radial position vector, and the circle diameter, d. Here, the radial distance to the first and last circle are already known, since their centers lie on the inner and outer circle, respectively. Following [42], the shape of the spline is now obtained by interpolation through the circle centers, while the width is obtained by interpolation of the circle diameters.

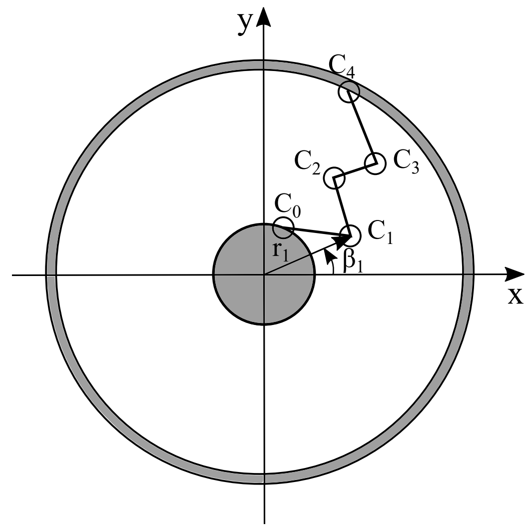


Figure 17: Representation of the compliant annular design domain with 5 interpolation circles. Figure adapted from [43] with permission from ASME.

Hence, if one wants to optimise the used material, it is better to choose a variable width spline.

3.2.3 Working direction and material

Until now, only mechanisms that work in one angular direction were discussed. It is, however, shown in [44] that it is possible to make the compliant mechanism work in both angular directions. This can be done by first designing the beams that need to be used in one direction and then the ones for the other direction. This implies that there is always an even number of curved beams in the annular design.

The choice of material is crucial in the design of a compliant CTM, since it determines a lot of factors, like e.g.,

- Torque level.
- Possible deflection.
- Flatness.
- Hysteresis.
- Stress relaxation.
- Weight.

One should, however, note that not all criteria can be optimised, since some counteract each other. Therefore, the application and its main requirements should be known beforehand. Hysteresis and stress relaxation are for example problems which do not occur with linear materials like steel, aluminium, etc. [45] and they also provide higher torque levels, but one should take into account that not only the weight will be higher than for their polymer counterparts, but also the range of deflection will be severely limited [46], due to the limited strain of the material.

3.2.4 Number of segments and links

The number of segments (the number of data points that are used) and the number of links (the number of curved beams) are the main denominators of the topology.

From [30], it follows that the number of segments has only an influence on the stress level inside the curved beams. The higher the number of segments, the better the stress can be distributed and hence the lower the maximal stress. No significant change could be found for the torque ripple when the number of segments and links were changed.

For the number of links it was found that, similar to the number of segments, the stress can be reduced if the number of links increases. The number of links has, however, also an influence on the ripple, since the torque ripple increases if the number of links increases [43].

3.2.5 Alignment

One should also note that due to the fact that all parts of the constant torque mechanism are compliant, it is best to add a carrier. This carrier serves to align the centre axes of the inner and outer ring, which is essential for joint mechanisms (i.e. input and output have the same axis of rotation).

Prototypes of this mechanism have been made by [43, 44, 47, 48] which all show that this concept produces a small torque ripple, but also a low torque and a limited rotational range.

3.3 Pre-compressed Beam Mechanisms

The curved beam suffers from the fact that a significant part of their rotational range is wasted by the pretensioning area. This can, however, not be avoided, since no force/torque can be generated if there is no motion. A possible way to overcome this is to apply a virtual movement to the beams, such that they already achieve the desired torque. This virtual movement can be obtained by pre-compressing the beams that connect the in- and output. By doing so, an ideal $T-\theta$ curve can be achieved as shown in Fig. 18.

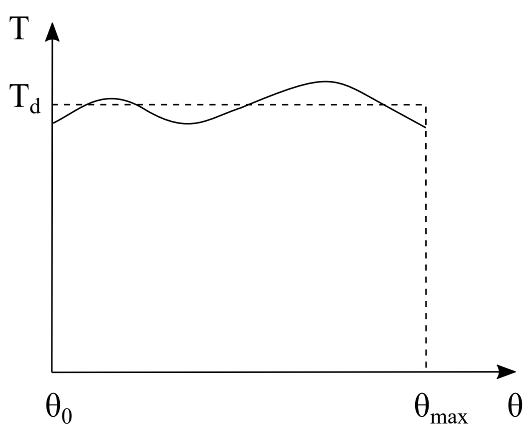
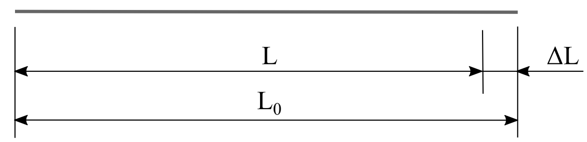
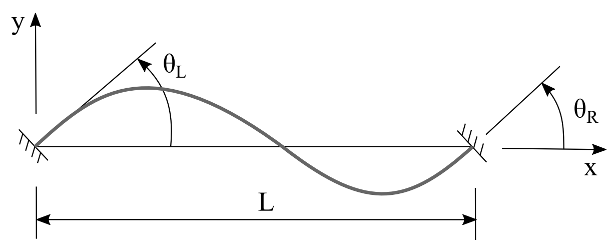


Figure 18: Representation of a realistic $T-\theta$ curve for a Pre-compressed compliant Constant Torque Mechanism. Here T_d represents the desired torque level and θ_{max} the maximal deflection of the CTM.

In [49,50] such Pre-compressed Beams were designed to get a compliant CTM. The design was done using finite element software where some input parameters have to be chosen (material, width of the beams, allowed axial compression of the initial beam, the desired rotation angle of the CTM and the inclination angle between the beam and the in-and output rings) such that the design parameters of the pre-compressed beam are generated considering the stress limits. These final generated design parameters, which are shown in Fig. 19, are ΔL, θ_l and θ_R, which represent the axial compression, the inclination angle on the left side and on the right side of the buckled beam, respectively. For this type of beam, spring steel is usually used, since it allows to undergo large stresses.



(a) The undeformed beam.



(b) The pre-compressed beam.

Figure 19: Representation of the pre-compressed beam in undeformed (a) and deformed (b) state together with the parameters necessary to describe them.

The described works, however, only work in one angular direction. In order to make the behaviour of the CTM bidirectional two separate CTMs are placed back-to-back, which is e.g., also done in [51].

3.4 Bistable Beam Mechanisms

The last type of beams that are discussed within the distributed compliance category is the *Bistable Beam CTM*. This type distinguishes itself by its simple design, using only straight beams to connect the inner- and outer ring, as shown in Fig. 20. This simple design contrasts with the complex manufacturing of the Curved and Pre-compressed Beam CTMs.

To achieve a constant torque this mechanism uses the fact that bistable beams can have both positive- or negative-stiffness behaviour in their post-buckling region [52–54]. Usually a bistable beam has a negative stiffness in the post-buckled state, but by manipulating correctly the beam parameters (width, thickness, length and inclination angle) using a finite element software, a region of zero stiffness and hence constant torque can be created.

In the current form, polymers are used in order to not

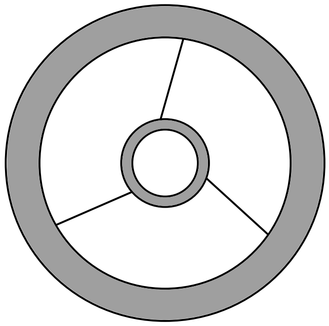


Figure 20: Graphical representation of a Bistable Beam CTM.

break after buckling, but they limit the produce torque. However, based on the works done for bistable beam based Constant Force Mechanisms it would be possible to use engineering metals as well.

3.5 Conclusion

The fact that the entire structure is meant to be flexible imposes certain advantages and disadvantages among which several are listed below:

Pros:

- Low weight.
- Compact.
- Low friction.
- No backlash.
- No need of lubrication.
- Low wear.
- Easy to miniaturise.
- Reduction of vibration.

Cons:

- Limited rotation.
- Dependent on material properties.
- Non-linear motion.
- Challenging design.

When taking a closer look to the individual types, it can be seen that both the torque and rotational range of all three types are limited. The Curved Beam CTMs can reach approximately $0.1Nm$, but achieve only a rotational range of $40°$. The desired/designed torque is not even precise due to the non-linearity of the used materials.

Regarding the Pre-compressed Beam CTMS, higher precision is reached for the torque level and the possible deflection is increased to around $70°$, but this at the cost of a possible torque level of approximately a factor 10 lower. Here, the manufacturing is also not straightforward, since metal beams have to be pre-compressed into complex shapes.

The Bistable Beam CTMS, on the other hand, go higher in terms of torque level and also have a simpler design since they only use straight beams. However, this imposes a severely reduced rotational range to around $10 - 12°$.

4 C-shaped Spring CTM

C-shaped Springs are the first type of constant torque mechanisms that need an input- and output axis that is not coaxial. For this type, the elastic deformation of flexure elements is used, but still a rigid connection is required.

C-shaped Springs are, as mentioned in [55], planar, very flexible elastic beams which are, in an undeformed configuration, a part of a circle. Its free ends are subjected to loads of constant direction. They can also be classified under the term of spiral springs, but their spiral shapes are not always in the same direction nor with the same distance between the coils.

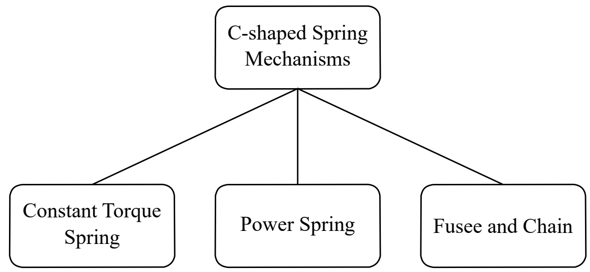


Figure 21: Classification of the different types of C-shaped Spring CTMs.

In this section three types of *C-shaped Spring Mechanisms* will be introduced that can be used as CTM, namely the *Constant Torque Spring*, the *Power spring* and the *Fusee and Chain*. This division is shown in Fig. 21.

4.1 Constant Torque Spring

The best known C-shaped Spring that can be used as CTM is a so-called *'Constant Torque Spring'* (a.k.a. a constant torque motor spring). This is a flat strip of spring material, which is formed into a coil with a virtually constant radius and stored on a compact *Storage drum*. When pulling the free end of a constant torque spring over another drum, it wants to go back to its initial coiled shape. The force that is produced by the spring to counteract this uncoiling, is near constant over the entire deflection range. This makes that the overall torque production becomes also constant. In practice, the free end of the coil is fixed to another (usually larger) *Output drum* (see Fig. 22).

This connection can be either done in the same direction (A-type motor spring) or in reverse (B-type motor spring) [56] (Fig. 23). The constant torque is generated through the fact that the spring always wants to attain its natural curvature and hence imposes a constant counter torque for the movements induced in the output drum. These two types are explained further hereunder.

A-motor [57]

The A-motor configuration has a limited internal stress since the metal strip is coiled in its natural way around both drums. Due to this, however, it produces the lowest

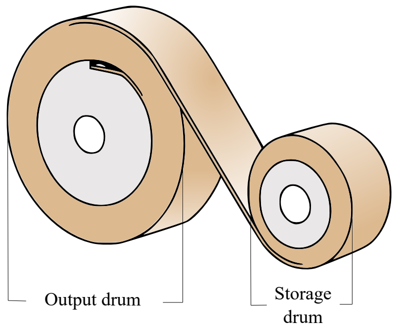


Figure 22: Graphical view of a Constant Torque spring. Here, the left part represents the output drum and the right part, the storage drum.

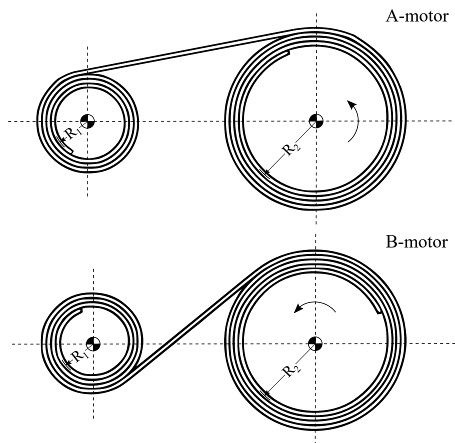


Figure 23: The different layouts of a constant torque spring, i.e., A-motor arrangement (top) and B-motor arrangement (bottom). Figure adapted from [56] with permission from Manfred Meissner and Klaus Wanke.

torque of both types, which also makes that this configuration is used the least. The torque that a spring produces in this configuration can be calculated with the use of the E-modulus of the spring material (E), the width of the metal strip (b), the thickness of the metal strip (t), the inner radius of the storage drum (R_1) and the inner radius of the output drum (R_2). The torque of a constant torque spring in the A-motor configuration is given by

$$T = \frac{Ebt^3 \left(\frac{1}{R_1} - \frac{1}{R_2}\right)^2 R_2}{26,4} \tag{3}$$

The stress that this torque produces in the material can be calculated by

$$\sigma = \frac{Et}{2r_0} \tag{4}$$

In this equation, the natural internal radius of the spring coil is also needed (r_0).

B-motor [58–62]

The B-motor configuration, on the other hand, produces the highest torque of both types. This implies that this configuration is mostly used in applications requiring significant torque and energy (e.g., space applications [10–12,14] and robotics [3,5]). The torque of a constant torque spring in the B-motor configuration is given by

$$T = \frac{Ebt^3 \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^2 R_2}{26,4} \tag{5}$$

It follows that the corresponding stress in the material can be obtained from

$$\sigma = \frac{Et\left(r_0 + R_2\right)}{2r_0R_2} \tag{6}$$

For both configurations it is recommended to have an inclination of around 110° for the strip between the two drums in order to optimise the lifetime and avoid too much hysteresis [10]. The following equation can also be used to calculate the perfect distance between the axes of the two drums

$$c = \sqrt{\frac{\left(r_0 + R_2\right)^3 + \left(r_0R_2\right)^2}{R_2}} \tag{7}$$

It is also recommended to always use an arrangement for which $\frac{r_0}{t} > 50$ in order to increase the lifetime [63].

Here, r_0 represents the natural inner radius of the constant torque spring when it is not wound on an arbour and t represents the thickness of the metal strip.

This type of CTM, which can easily be bought to some specialised spring manufacturers like Spiroflex [64], Vulcan Spring [65] and Ametek [66] under the names of respectively *motor torque springs*, *Contorque* and *Neg'ator*. In their catalogues, it can be seen that constant torque springs exhibit extremely large deflection and torque ranges which go up to 27 working turns of deflection and a torque of 10.10Nm. If necessary, this can, however, also be customised up to even higher torque level while keeping a limited torque ripple.

The main disadvantage of this type of CTM is, however, that it is prone to low-cycle fatigue, which makes that usually only a life-time is guaranteed of 20.000 cycles, which can go up to 50.000 in the range of low torque, but decreases down to 5.000 for the high-torque springs.

4.2 Power Spring

Power springs, or *Mainsprings* as they tend to be called in the horology community [67], are just like the constant torque springs made of a flat strip of spring material.

However, it can be seen in Fig. 24 that the behaviour is slightly different. When comparing both C-shaped springs, it can be noted that the constant torque spring can be used in almost its entire rotational range, which is not the case for power springs [68–72]. A solution consists in only using the limited part of the working range where the delivered torque is approximately constant [73] as indicated in Fig. 24. In-depth instructions on how to only use this useful working range are mentioned in [69].

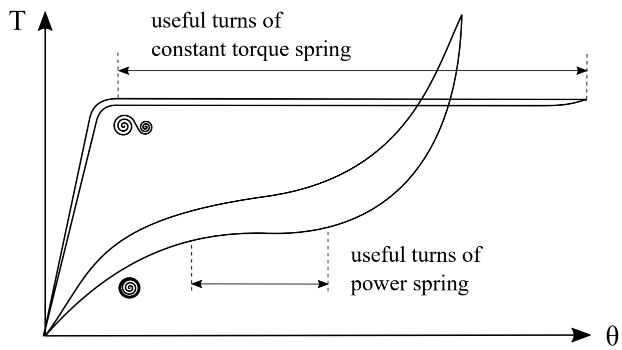


Figure 24: Approximative torque-deflection behaviour for constant torque springs and power springs together with an indication in which range they can be used as constant torque mechanism (CTM). Here, it can be seen that the range of constant torque springs is larger and provides a higher torque level. Figure adapted from [74] with permission from Ming Tai Industrial.

Within the category of power springs, there are two different types which are in the industry denoted as *Conventional Power springs* and *Pre-stressed Power springs*.

4.2.1 Conventional Power Springs

For this type, the free end of the metal strip is connected to an inner arbour and the rest of the spring is tightly wound and connected against a fixed outer circular case [75], as shown in Fig. 25.

Figure 25: Graphical view of a Conventional Power Spring [76].

This type of Power Spring is mainly used in applications where compactness is crucial, since it is possible to use this where the input- and output axis are coaxial.

4.2.2 Pre-stressed Power Springs

The Pre-stressed Power Spring (also known under the name *Spir'ator* when they come from the manufacturer Ametek [66]), on the other hand, does not have a shape that only spirals in one direction like for the conventional one, but it has a part that is wound in the reverse direction, as shown in Fig. 26. This is possible due to the pre-stressing, which allows to achieve up to 25% more torque than a conventional power spring, and also has a flatter torque gradient [77, 78]. The consequence of the pre-stressing is, however, that the lifetime decreases.

Figure 26: Graphical view of a Pre-stressed Power Spring [79].

4.3 Fusee and Chain

The previous power springs had the disadvantage that they could only operate in a limited range as CTM. In the watch industry, however, they found a way to solve this problem by attaching a variable radius drum (Fusee) to a conventional power spring with a chain [67–69].

This *Fusee and Chain* Mechanism, as shown in Fig. 27, is not really conical but has a bell-like shape and tries to compensate for the decrease in torque from the power spring as it unwinds by changing the radius of the axis it drives [80]. The way this mechanism compensates the decrease in torque can be compared to a continuously variable transmission (CVT) and enables that the entire working range becomes useful again. It has the advantage that it is designed such that it always stays in its constant torque region, which makes that no pre-load region is felt during operation.

4.4 Conclusion

In general, C-shaped Springs have good characteristics to be used as a constant torque mechanism (CTM), since they can provide rather high torques (up to 10Nm) and a large rotational range. For constant torque springs this goes up to 20-30 complete turns, which makes them unmatched in the torque-deflection range, while being rather compact. The only, but significant downside of this type of CTMs is that they have a very limited lifetime (max. 50 000 cycles when

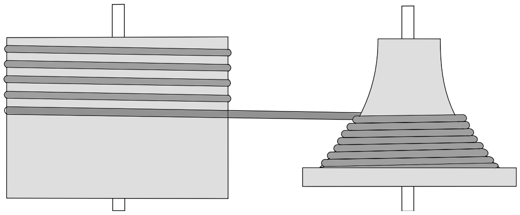


Figure 27: Representation of the Fusee and Chain Mechanism. On the left, the barrel is shown, which has a mainspring inside. This barrel is connected with a chain to the Fusee on the right.

not stressed too much), which is due to the low cycle fatigue that takes place in these metal strips [70, 71].

Power Springs also have the downside of a limited lifetime, but this is less severe since it varies between 100000-250000 cycles. The range in which they provide constant torque is, however, not as large as for constant torque springs.

The last category is the Fusee and Chain mechanism. This was created for horology and hence usually does not display high torques. However, it provides an extensive constant torque range. An industrial version of this can be found under the form of a *Spring Tool Balancer* [81]. This spring tool balancer works as the fusee part of the mechanism and hence produces constant force [82]. This system can then easily be transformed into a constant torque by using a pulley as barrel. This will pose no extra problems since there is already a wire/cable attached to the output of the spring tool balancer. By doing so, higher torques can be created than what is possible with their horology counterparts. One should not that for a spring tool balancer the spiral spring is attached to the axis of the fusee, whereas a regular fusee and chain mechanism has it attached to the axis of the barrel.

5 Elastic Deformation Mechanisms

Elastic deformation mechanisms are, as the name suggests, mechanisms that generate constant torque by using the very large strain properties of the materials they are composed of. Due to their large strains they are often used as mechanical batteries for toys, e.g., small cars or model airplanes, which is why they are often depicted as *Elastic motors*.

This type of CTM can be divided into two main subtypes, namely *Twisted Elastics* and *Wound-up Elastics* (Fig. 28).

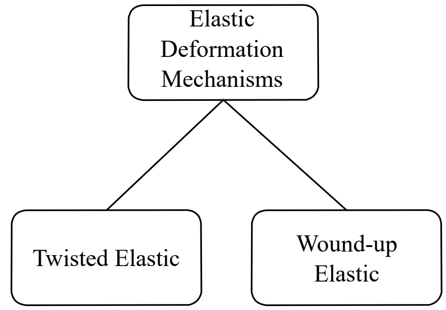


Figure 28: Classification of the different types of Elastic Deformation CTMs.

5.1 Twisted Elastic

This type of powering device is made by attaching an elastic loop, usually rubber, at one side through a hook fixed on a propeller shaft and at the other side to a second hook at the tail of the craft (Fig. 29).

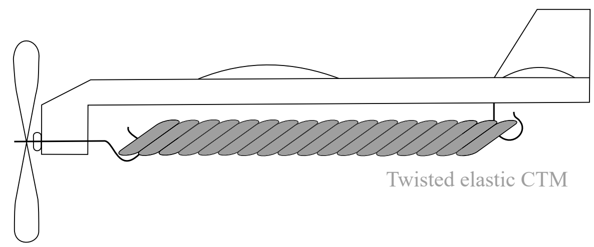


Figure 29: Visual representation of a Twisted Elastic CTM applied as elastic motor on a toy airplane.

By twisting the rubber, a skein is created which transforms gradually into a row of knots throughout the entire length of the rubber as it is twisted further. This represents the first stage. When the entire length is filled with knots, the second stage starts and new knots start to form in the already formed knots. When the entire length is filled, the rubber is at its maximum strain.

When the rubber is released at this point, a torque curve is generated as shown in Fig. 30, which provides the mechanical power to propel the aeroplane. This torque curve starts with an initial high torque, and proceeds afterwards with a region of slowly declining torque which represent a sort of constant torque region. After some time, the generated torque goes back to zero when the rubber is untwisted [83, 84].

Figure 30: Approximated representation of the torque-time curve of a Twisted Elastic CTM.

However, the generated torque is most of the time very unstable due to the internal friction in the knots. Therefore, the constant torque region is not really constant, which is one of the reasons why this type of constant torque is only used for the propulsion of small toys. For this application, it is less crucial to have a stable constant torque region. However, such mechanism becomes more and more used in robotics as well, better known under the name of *Twisted String Actuators* [85–88].

5.2 Wound-up Elastic

In order to solve the reliability of the constant torque production, a system was designed in [83, 84] that couples two drums that are tied together with an elastic wire, as shown in Fig. 31.

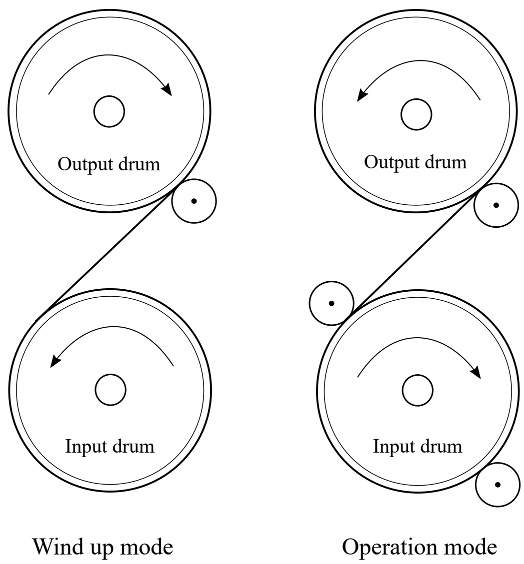


Figure 31: Conceptual working principle of a Wound-up Elastic Constant Torque Mechanism. On the left, the wind-up mode is displayed and on the right, the operation mode.

In the wind-up mode (left part of Fig. 31), an elastic wire hangs initially slack around the reel of the output drum. By using a motor the input drum starts to turn counter-clockwise and hence the output drum clockwise. Due to the fact that the input- and output shaft are connected with a gearbox or a cog belt such that the input drum turns n times faster than the output drum, the elastic wire is stretched up to n times its initial length on the input drum. In order to make optimal use of the elastic material, the stretched wire should be close to full tension when its completely wound on the input drum. It can also be seen that a roller is added on the output drum, which is used to avoid wire slipping.

In the operation mode (right part of Fig. 31), each unit length (i.e., the length of the wire which hangs in between the two drums) of the elastic is allowed to relax back to its normal state. While doing so, a torque (and work) is generated at the output drum until the wire is back to its unstressed state, i.e., when the input drum is completely unwound. Note that, during this process, the rollers always need to be included to avoid slippage. In the operation mode, they can be found at more places than for the wind-up mode, since the chances are higher that slip might happen in the operation mode. In order to add this anti-slip mechanism in an easy way without too many moving parts and without making it too bulky, one can add end plates on the reel such that the distinct unit lengths can be separated. Each disc has a small opening where the elastic wire/strip fits through, but prevents it from slipping. This example is shown in Fig. 32.

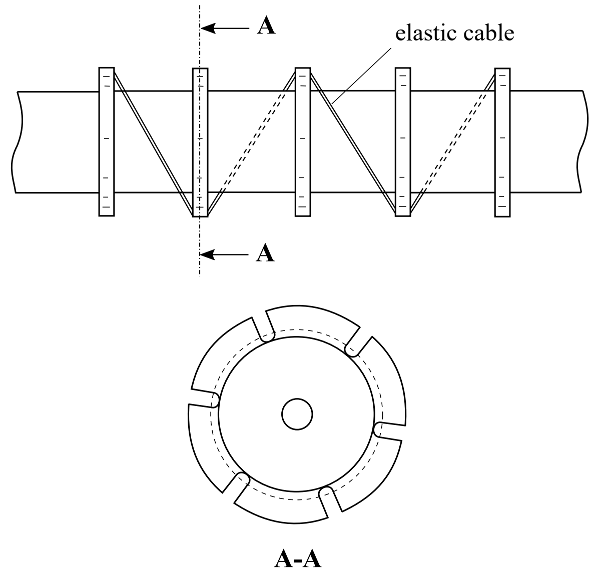


Figure 32: Graphical representation of a Wound-up Elastic CTM with plates added to avoid friction.

This design allows to produce a stable sawtooth torque-shape, as shown in Fig. 33. In this graph the peak torque represents the initial point where a unit length is starting to transfer its energy towards the output drum and is equal to the tension in the wire multiplied with the radius of the reel. The lowest torque in the graph represents the zone in which one of the unit lengths is completely unwound. The average torque is half that of the maximum value and is constant over time while in operation mode [84].

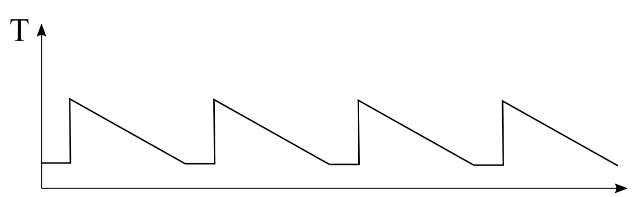


Figure 33: Graphical representation of the output torque of a Wound-up Elastic CTM as a function of the time.

The behaviour of this type of elastic motor is more reliable, since there is no excessive friction during the operation, which in contrast, was present for the twisting method.

An analogy for the working principle of a wound up elastic can also be taken from a steam engine, which has a steam supply at constant pressure. There, "portions of steam are fed to a cylinder where the steam expands to generate work (pressure times change in volume) by pushing a cylinder back to turn a wheel. When the expansion is complete the steam is exhausted and the process repeated" [84].

6 Constant Force-based solutions

The last category, i.e, the Constant Force Mechanisms (CFM), will finally be discussed, as they can be extended towards Constant Torque Mechanisms with some adjustments.

Due to the fact that CFMs [52] are mainly used for linear movements, the only adjustment needed is to transform the linear motion into a rotational one to get a CTM. This conversion should, however, allow a constant speed ratio and a relatively good backdrivability. If these characteristics are not met, the constant force will not be converted into constant torque. Mechanisms like e.g. a worm wheel or lead screws will thus be omitted here, since they are too challenging to backdrive.

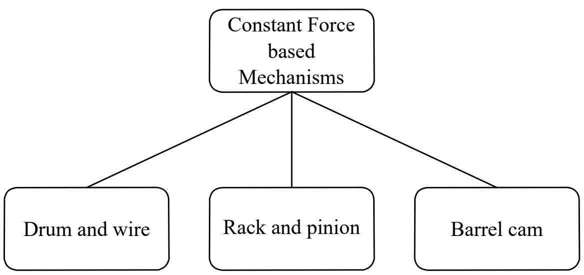


Figure 34: Classification of the different types of Constant Force-based CTMs.

In this section, common examples of mechanisms are discussed which can properly convert the linear motion of the CFMs into a rotation such that a CTM can be created. These mechanisms are *Drum and wire mechanisms*, *Rack and pinion mechanisms* and *Barrel cam mechanisms*, which are shown in Fig. 34. The interested reader can, however, find other examples for the conversion of linear into rotational motion using some basic mechanisms [89] or some more complex ones [90, 91].

6.1 Drum and wire

A first way to transform linear motion to rotational is by connecting the output of a CFM to a constant radius pulley. This can be done through wires, as shown in Fig. 35.

The wires should, however, be stiff enough to avoid too much flexibility, which would make the torque non-constant. The level of the constant torque is determined by the radius of the pulley.

This is similar to the working of a gear transmission, since one can choose either a high torque and small angular deflection (when a high radius drum is used) or low torque and high angular deflection (when a small radius drum is used).

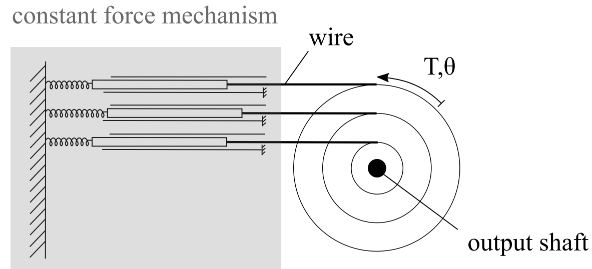


Figure 35: Graphical representation of how a Constant Torque Mechanism can be formed by combining a Constant Force Mechanism and a drum and wire. Here, a drum is shown with different radii on the right.

6.2 Rack and pinion

The second possibility to transform linear to rotational motion is to use a rack and pinion, shown in Fig. 36. Here, the constant force mechanism should be coupled to the rack, such that a movement of the CFM will make the rack shifts either to the left or right and hence induce a rotational motion at the pinion such that a constant torque is created.

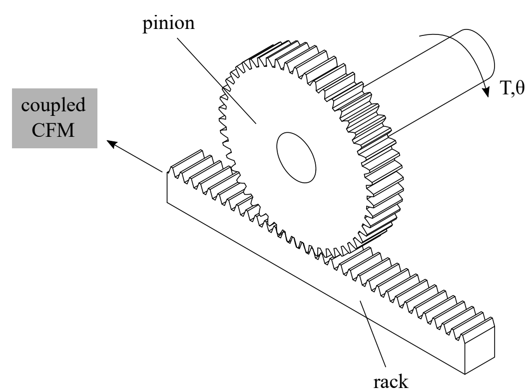


Figure 36: Graphical representation of how a Constant Torque Mechanism can be made by combining a Constant Force Mechanism (CFM) and a rack and pinion. Here, the rack is coupled to a CFM such that a constant torque is generated at the pinion.

6.3 Barrel cam

The last option of conversion is a barrel cam. This type of cam, which is shown in Fig. 37, is actually a cylinder in which a pattern is cut out. This pattern is followed by a roller [92]. This roller is connected to a slider which can move on a linear track.

By coupling a CFM to the connection of this slider, a rotational motion is created. Note that the cam should be designed in such a way that the transfer function between the linear and rotational movement is linear.

	Max. Torque level [Nm]	Max. Deflection [°]	Torque ripple	Lifetime	Specific energy [J/kg]	Price/Complexity
Distributed Compliance Mechanisms						
Curved Beam CTMs	0.3	40	- -	+	4	++
Pre-compressed Beam CTMs	0.01	70	+	0	0,05	-
Bistable Beam CTMs	0.2	12	+	+	1	++
Lumped Compliance Mechanisms						
Stiffness-combination CTMs	0.14	75	++	++	Highly dependant on architecture	-
Cam-based CTMs	20	270	++	++	Highly dependant on architecture	0
Friction-based CTMs	dependent of friction	∞	++	0/+	Not applicable	–/0
C-shaped Spring Mechanisms						
Constant Torque Springs	10.1	10 000	++	- -	470 (spring) / 430 (spring+drums)	++
Power Springs	6	2 000	0	0	300	++
Fusee and Chain	7	8 000	++	++	75 [81]	–
Elastic Deformation Mechanisms						
Twisted Elastics	0.1	++	– –	–	6600 [93]	++
Wound-up Elastics	1	++	0	0	2200	+

Table 2: Comparison of all the different types of CTMs. The values listed here are indications, since optimisation can slightly change those values. However, the order of magnitude and the relative difference between the different categories are valid. Some metrics are scored by using one of the following symbols: '- -', '-', '0', '+' and '++'. They stand respectively for: 'not good at all', 'rather bad', 'ok', 'good' and 'very good'.

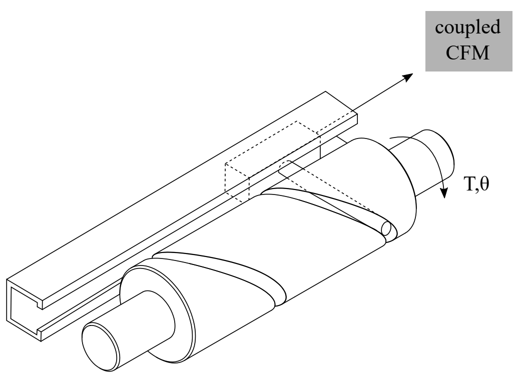


Figure 37: Graphical representation of how a Constant Torque Mechanism can be formed by combining a Constant Force Mechanism (CFM) and a barrel cam. Here, the nut is coupled to a CFM such that a constant torque is generated at the barrel cam.

7 Comparison

In order to properly compare all types of constant torque mechanisms among each other, some metrics need to be chosen which provide the most intel. First, we chose to compare the torque and deflection range of all the mechanisms. More specifically, we compare the range and the level on which constant torque is produced. These are one of the most important metrics, since they decide on the possible working area. Next, the precision with which they can achieve their desired torque level is compared, i.e. how much ripple is present in the torque. For this ripple, the value is given as an indication, since all systems do not perform similarly and their behaviour also depends on the shape of the ripple. Another important comparison criteria is the lifetime of the mechanism before something breaks, since it will decide in which potential applications it can be implemented. A mechanism to deploy satellites needs to be used only once, which makes lifetime irrelevant, but this low demand of cycles is not the case for most applications. This makes that it is important to also take this metric into account.

The next metric is the specific energy or the energy content per mass. This metric is chosen instead of the energy per volume since the mass is independent of the architecture of the CTM. For some CTM types, no value is reported since the metric is only applicable for systems providing energy, namely the so-called *Power Assistance* CTMs. This metric is also introduced such that afterwards the torque can be normalised and that the possible energy content of a certain mechanism can be evaluated. The last metrics are the price and complexity. Those metrics are quite challenging to assess and quantify since they are subjective. Therefore, a qualitative indication, i.e., -/0/+, is given which refers to poor, neutral and good, respectively.

An overview of the scored CTM types based on these metrics is shown in Table 2. The values listed here are indications, since optimisation can sightly change some values. However, the order of magnitude and the relative difference among the different categories are valid.

In Table 2, it can be seen that the Distributed Compliance Mechanisms show rather poor characteristics for each metric since they cannot provide a high torque, deflection and precision. A significant part of their working range is also used as pre-load region. Their only advantage is the fact that most of them can be 3D printed which results in a high score for price/complexity.

Lumped Compliance Mechanisms show better characteristics. However, they cannot be properly compared to the other CTM types in terms of torque and deflection, since they are highly dependent on the chosen architecture, materials, and springs. The friction-based mechanisms are even more difficult to compare, since they are only used as torque limiters, i.e., for the application of torque stabilisation. This is also the reason why no specific energy is mentioned. This category also shows a very consistent constant torque behaviour, which is probably due to the fact that it is a crucial part of their task.

When looking at the C-shaped Springs it can immediately be seen that, in terms of torque, deflection and precision, this is the category to use if power assistance is required. In this category both constant torque and power springs can be bought to specialised spring manufacturers. This makes that they are also rather easy to implement in a design. The constant torque springs of these systems provide overall the best characteristics with a constant torque of about $10Nm$ for around $20-30$ turns, together with a good precision and specific energy, higher than conventional springs [94]. This, however, results in one serious drawback, namely the lifetime. Depending on the chosen spring the lifetime of a constant torque spring ranges from 20000 to 50000 cycles, which is considerably lower than the millions of cycles that are possible with linear springs. Power springs also display good characteristics, with a slightly lower constant torque and a shorter deflection range, but in return provide an increased lifetime which varies between 100000 and 250000 cycles depending on the spring used.

The Fusee and Chain mechanism, on the other hand, is rather challenging to design and make when used in horology. It is also not capable of providing high torques. However, when looking at the industrial version of this mechanism, namely the spring tool balancer, it can be seen that, for a volume comparable to the other mechanisms, it delivers a decent torque of around $7Nm$ together with an extensive working range in which the constant torque is delivered, this however, at the cost of its bulkiness. In general the C-shaped springs perform very well, but improvements are still possible with the use of e.g., advanced materials like fibreglass instead of a metal spring strip [95].

When looking at the last category of Elastic Deformation Mechanisms, it can be seen that they provide a decent torque with a rotational range that is only dependent on the amount of material. Therefore, this metric is scored '++' in the table. Also price/complexity are received a high score, since only the elastic material and a support piece (hooks or drums) are needed. With some back-of-the-envelope calculations based on the assumptions that rubber bands would be used for the twisted elastics, nylon for the wound up elastics and a drum thickness of 2mm, it is found that both subcategories provide rather large specific energy.

In terms of lifetime, the score is material dependent. If, e.g., the rubber bands are placed under sunlight, the rubber could suffer from abrasion. Another downside is the torque precision, which is rather poor for the twisted elastics. For the wound-up elastics, the torque precision is better according to the documentation. However, no experiments are found providing quantified data to back it up. Wound-up elastics are therefore promising for the development of CTMs, but further research should be conducted to quantify its specific characteristics.

In order to simplify the choice of a constant torque mechanism for a specific application, a flowchart is made in Fig. 38 that can help designers in choosing the proper mechanism.

8 Conclusion and reflection on open challenges

This paper has provided an overview of the most common Constant Torque Mechanisms, their mechanical configurations, and possible applications. First, a classification was given based on the two primary types of function, namely Power Assistance and Torque Stabilisation. In the context of the former, the principle of Zero Torque Shift was shown to support the use of CTMs across a range of applications where high payloads need to be handled and/or assistance needs to be provided.

Second, an alternative classification of CTMs by structure highlighted five primary categories, namely Lumped Compliance, Distributed Compliance, C-shaped Spring, Elastic Deformation, and Constant Force-based Mechanisms. Here, differences in structural characteristics and performance metrics, such as torque range, deflection range, and precision, were described in detail and formed a basis for a summary comparison (Table 2) between different types and subtypes, as well as a flow chart (Fig. 38) guiding the selection of suitable CTMs for either of the two types of function.

Whereas extensive research has resulted in near-optimal performance for several types of CTMs, it is clear from the preceding discussion that there is still room for improvement for other types that, although less researched, do not necessarily have less potential. An example of the former category, C-shaped Spring Mechanisms have been used and investigated for decades in both academia and industry due to their desirable characteristics regarding torque and deflection. Indeed, one concludes from Table 2 that the C-shaped Spring Mechanism is the category with the greatest potential for Power Assistance CTM applications due to its high maximum torque and large maximum deflection. On the other hand, the less common Lumped Compliance Mechanisms can be useful for some specific applications, but have as a downside that they are bulky and consist of many components. While the constant torque range of Friction-based Mechanisms is wide, they can only be used as torque limiters and not as torque providers.

CTM research is mostly conducted in the subfield of Distributed Compliance Mechanisms. Here, improvements in manufacturing techniques allow straightforward production of complex-shaped mechanisms that are lightweight

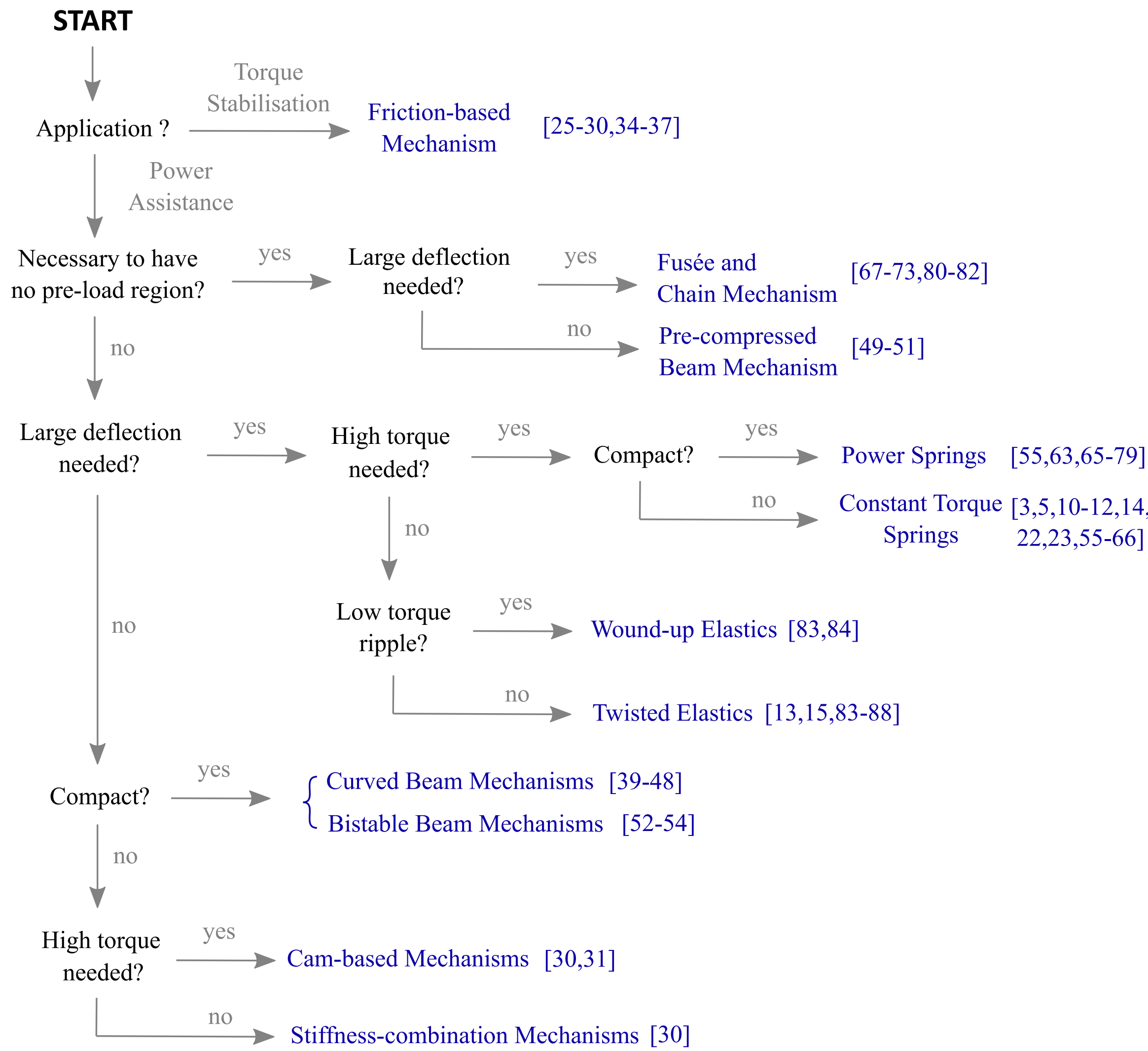


Figure 38: Flow chart for selecting a Constant Torque Mechanism. This chart is a tool to help select a specific constant torque mechanism for a desired application. References are also included for the different mechanisms on the right.

and compact, since no connection pieces are required. For the subclass of Pre-compressed Beam Mechanisms, the absence of a pre-load region allows immediate generation of the desired constant torque. Nevertheless, unless advances are made on the material level, the utility of Distributed Compliance Mechanisms is limited to applications requiring only a small rotational range, small energy content, and low torque.

Elastic Deformation Mechanisms show great potential for future use due to their high specific energy, but more research is required to overcome various technical challenges. As an example, Twisted Elastic Mechanisms are currently researched for robotic applications under the name of twisted string actuators. These CTMs are preferred due to their compactness, reduced price, simple design and light weight, but current realisations cannot reliably produce a constant torque due to effects of friction, creep, and material hysteresis.

According to the authors, the most interesting subclass to explore is the Wound-up Elastic CTM due to its high specific energy and compact, high-capacity energy storage. Other than a few patents, almost no research has been conducted on these mechanisms despite the fact that they present all the benefits of the Twisted Elastics while also being able to provide constant torque over a larger range.

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