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CONCEPTUAL DESIGN EVALUATION OF DIFFERENT FRICTION DEVICES THROUGH THE USE OF AXIOMATIC DESIGN.

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ABSTRACT

Defining the best design solutions is a current issue for a lot of design teams. This issue is becoming more and more important due to the high standard requested to new products and to the need of meeting customer satisfaction with the lowest cost. Defining critical functions of a product by meeting customer satisfaction and reaching the goals of a new project is a critical activity in order to provide the success of the company and the business efficacy. The identification of the best design, according to the two axioms, permits companies to minimize the high costs related to trial and error approach, avoiding mistakes and designing goods systematically. In this paper Axiomatic Design principles are used to evaluate the agreement level to the best design of some concepts concerning a friction device of a mechanism. The proposed friction devices work to avoid overloads on the mechanism used to release the spare wheel of a vehicle. This approach consists of drawing the design matrix for each concept to compare them with the triangular or diagonal matrix. Such kinds of matrices are typical of a functional independence among critical functions, according with the theory of Axiomatic Design. Each concept will be evaluated also in terms of the information content according to the second axiom, in order to identify the design solution which maximizes the probability to verify the design requirements.

Keywords: Concept synthesis and evaluation, Concepts Choosing Process, Axioms agreement assessment.

1 INTRODUCTION

Choosing the best design, according to the axiomatic design theory, is increasingly important in modern engineering activities to reach maximum performance and customer satisfaction with economical convenience.

Choosing the wrong design could lead to product failures and high costs to investigate how to fix them. On the other hand, the many compromises needed during product design are often responsible for a non-optimal design and for a reduction in the design process efficiency (delays or cost rising). Several attempts have been made in order to develop the nearest design to the best one, like MADM or QFD approaches (e.g. in [Cavallini *et al.,* 2013], [Cavallini *et al.,*2013], [Jahan *et al.,* 2010], [Ulrich and Eppinger, 2011]). A non-optimal design could not be also effective to meet the customer requirements. Because of this, it is very important to set the main functional requirement (FR) at the higher level, i.e. what the device, or the concept, should do. According with the axiomatic theory several main FRs could be found by drawing a QFD matrix or executing customer interviews.

The aim of this paper is to drive towards a skimming selection of several concepts through the agreement evaluation of each concept to the best design condition.

2 SCOPE AND USED APPROACH

In this paper the authors are going to select a concept from a pool of possible solutions, evaluating the agreement level to the best design conditions described in the axiomatic design theory. These concepts are about a friction device used in the automotive industry to avoid overloads when the spare wheel of a vehicle is lowered or raised.

The friction device works when it is operated by the user who wants to raise or lower the spare wheel of his vehicle. The user has to apply a torque to a lever in order to unlock the wheel and lower it, or raise it until its lock. If the torque is excessive, the friction device will permit sliding between the parts which lead the input and the output of the motion.

The complete architecture of the friction device can be defined by decomposing the highest level FR and DP, creating hierarchies of FRs, DPs and PVs. This is done through zigzag mapping among these domains, according with what has been stated by Thompson [2013].

This case deals with one FR design since the main FR is "To transmit the torque without overloads" and it is common for all solutions. A way to achieve this main FR is a system able to maintain a selective contact between two surfaces (DP1 is common for all concepts). Such system shall permit to perform the selection between the no sliding condition and the sliding one depending on the amount of transmitted torque.

The main FR is further split into three different FRs at the second layer of zigzagging. These common FRs for all concepts are FR1.1 “To realize selection between sliding condition and no sliding one”, FR1.2 “To make adherent shapes and non-adherent ones” and FR1.3 ”To hold component parts linked”.

As previously stated, this friction device has the aim to avoid overloads in the mechanism, so it works linearly until the applied torque reach 50 Nm, than large sliding occur and the given torque fall down to values next to 0 Nm. Within the limit value of 50 Nm the behaviour of the device is almost linear and the ratio between the applied torque and the given one is 1. In Figure 1the curve which relates the applied torque and the given one is shown.

Several concepts are diversified by how they achieve these functions and in the following layers of zigzagging.

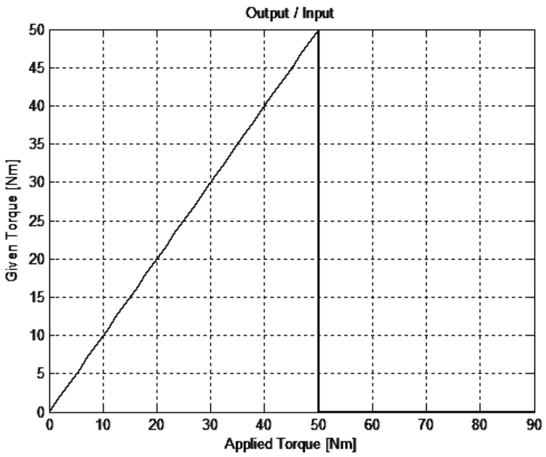

Figure 1 Relation between the applied torque and the given one to avoid overloads.

2.1 CONCEPT ONE: BELLEVILLE SPRINGS

The first concept is characterized by the Belleville springs to achieve the selection between the condition of torque transmission when the two surfaces are adherent without sliding, and the condition of no torque transmission with an amount of sliding between the two surfaces in contact.

In Figure 3, a section of this concept is shown and the component parts can be seen. Torque enters in the device through the cap. It is transmitted by the cap to the plates and gets out through the lower cogwheel, while the shaft is fixed. The first plate is coupled with the cap, so it can rotate with it,while it is kept in contact with the second plate by the springs pack at the upper side. The second plate has several pads on the upper surface that fill some grooves on the lower surface of the first one and its axial position along the shaft is fixed at the bottom side by a screwed support of the lower cogwheel. The coupling between the grooves and pads is shown in Figure 2.

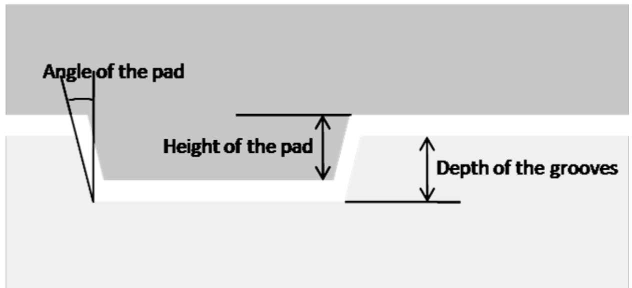

Figure 2 Coupling between grooves and pads.

The shaft presses the Belleville springs pack against the second plate, which stays in contact with the pads on the opposite surfaces of the first one. When the torque increases over the given limit of resistant torque, sliding occurs and a shift between the two surfaces, which are no longer adherent, takes place. When the torque increases over the given limit of resistant torque, sliding occur and a shift between the two surfaces, which are adherent no more, takes place. Sliding works in reducing the amount of transmitted torque until the adherence between pads and grooves is restored.

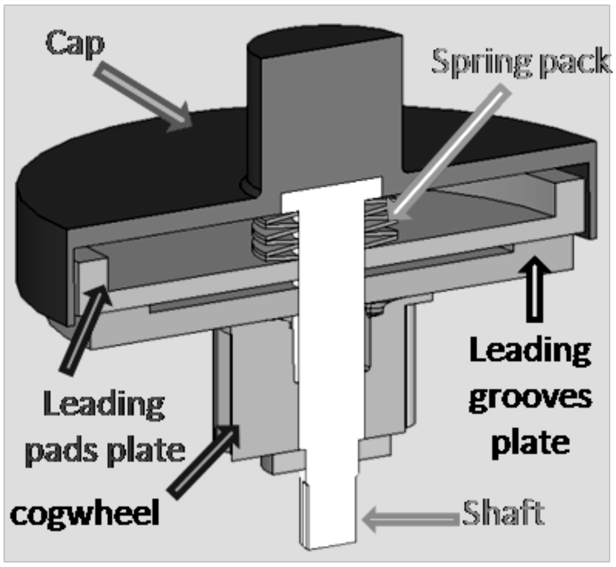

Figure 3 Friction device using Belleville springs.

Using the zigzagging method, the authors have mapped the functional and physical domains identifying some correlations among FRs and PDs. This has led to drawing the design matrix for the concept. The FRs of this mechanism further common ones are defined as follow:

FR1.1.1 To control the position of the pads
FR1.2.1 To turn the actuation torque in compression force above the spring
FR1.2.2 To apply the preload of the spring
FR1.2.3 To transmit the torque to the pads

The characteristic DPs further DP1 are defined as follow:

DP1.1 Belleville spring(s)
DP1.2 Grooves/pads system
DP1.3 Case
DP1.1.1 Spring stiffness
DP1.1.2 Spring free height
DP1.1.3 Number of springs

DP1.2.1 Height of the pads
DP1.2.2 Angle of the pads
DP1.2.3 Depth of the grooves
DP1.3.1 Height of the internal vane

In Table 1 the design matrix which relates the FRs and DPs vectors is reported.

	DP1	DP1.1	DP1.2	DP1.3	DP1.1.1	DP 1.1.2	DP 1.1.3	DP 1.2.1	DP1.2.2	DP1.2.3	DP 1.3.1
FR1	X										
FR1.1		X									
FR1.2			X								
FR1.3				X							
FR1.1.1					X			X	X	X	
FR1.2.1								X	X		
FR1.2.2						X	X			X	X
FR1.2.3										X	X

Table 1 Belleville Springs Design Matrix

2.2 CONCEPT TWO: HELICAL SPRINGS

The second concept is characterized by some helical springs. The motion enters through the shaped shaft and it is transmitted to the case (output) via springs. A cap (that is semi-transparent in the picture) has some linear guides to make the springs move only along the radial direction. The springs lead shaped blocks to fill some grooves in the internal side wall of the case. The springs keep these blocks pressed against the grooves of the case allowing the torque transmission. If the torque overcomes the given limit the helical springs will be compressed and the shaped blocks will get out the grooves reducing the amount of torque since it is transmitted no more. In Figure 4 a view of the device is shown with shaped blocks and helical springs.

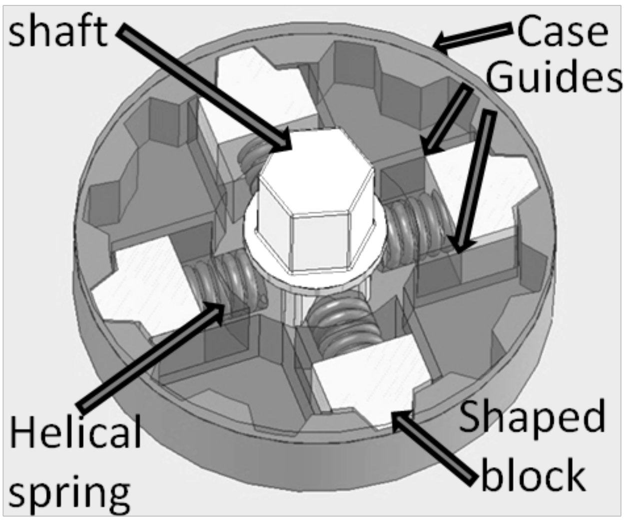

Figure 4 Friction device using helical springs.

The design of this solution is defined through the zigzagging method which can set a hierarchy among several layers of FRs and DPs. The DP1, FR1, FR1.1, FR1.2 and FR1.3 are the higher level which is common for all concepts.
The lower FRs of this mechanism are defined as follow:

FR1.1.1 To control the position of the blocks
FR1.1.2 To drive the springs
FR1.2.1 To turn the actuation force into a compression force on the spring
FR1.2.2 To apply the preload to the spring
FR1.2.3 To transmit the torque to the case

The characteristic DPs further DP1 are defined as follow:

DP1.1 Helical spring(s) and Cap
DP1.2 Shaped blocks
DP1.3 Containment casing
DP1.1.1 Spring(s) stiffness
DP1.1.2 Spring free height
DP1.1.3 Springs number
DP1.3.1 Height of the teeth
DP1.3.2 Angle of the teeth
DP1.3.3 Case diameter
DP1.4.1 Guides on the cap

In Table 2 are shown the correlations which link functional requirements and the adopted design solutions.

	DP1	DP1.1	DP1.2	DP1.3	DP1.1.1	DP 1.1.2	DP1.1.3	DP 1.3.1	DP1.3.2	DP1.3.3	DP 1.4.1
FR1	X										
FR1.1		X									
FR1.2			X	X							
FR1.3			X	X							
FR1.1.1					X		X	X	X	X	X
FR1.2.1								X	X		
FR1.2.2					X	X				X	
FR1.2.3								X	X		
FR1.1.2											X

Table 2 Helical Spring Concept Design Matrix.

2.3 CONCEPT THREE: FLAT SPRING

The third concept has a flat spring to achieve the selection between the sliding condition and the non sliding one. In this case the spring is a single shaped steel piece whose leading edges fill the grooves on the side wall of the case.
A shaped cap holds the stopping spring in its position. When torque raises over given limit, the spring elongation is such to make the leading edges overcome the grooves, losing the contact and decreasing transmitted torque until it will reach lower values. In Figure 5 the device is shown.
The design of this solution is defined through the zigzagging method which can set a hierarchy among several layers of FRs and DPs. The DP1, FR1, FR1.1, FR1.2 and FR1.3 are the higher level which is common for all concepts.
The lower FRs of this mechanism are defined as follow:

FR1.1.1 To control the spring edges position
FR1.1.2 To transmit the torque to the case
FR1.1.3 To constrain the spring
FR1.2.1 To turn the torque into a load over the spring
FR1.2.2 To apply a preload to the spring

The characteristic DPs further DP1 are defined as follow:

DP1.1 Flat spring
DP1.2 Containment casing
DP1.3 Cap
DP1.1.1 Spring stiffness
DP1.1.2 Spring free height
DP1.1.3 Spring number
DP1.2.1 Grooves depth
DP1.2.2 Angle of the grooves
DP1.2.3 Case diameter

DP1.3.1 Guides on the cap

In Table 3 are shown the adopted design solutions and their corresponding functional requirements.

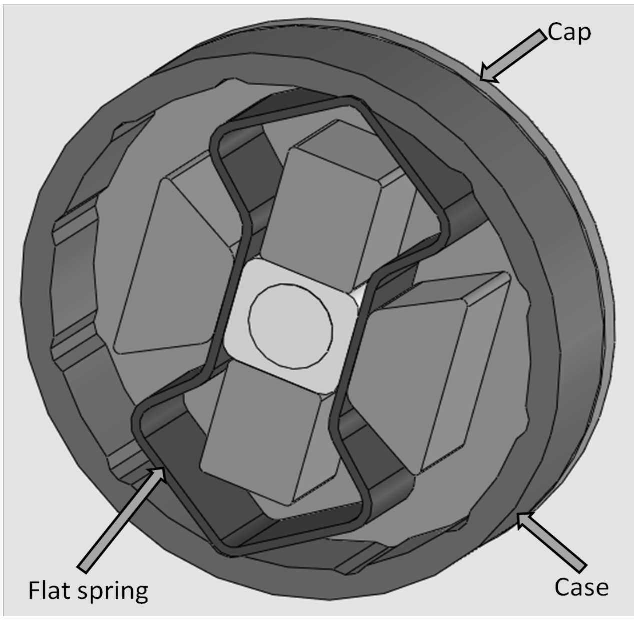

Figure 5 Friction device using flat spring.

	DP1	DP1.1	DP1.2	DP1.3	DP1.1.1	DP 1.1.2	DP1.1.3	DP 1.2.1	DP 1.2.2	DP1.2.3	DP 1.3.1
FR1	X										
FR1.1		X									
FR1.2		X	X	X							
FR1.3			X								
FR1.1.1					X		X	X	X	X	
FR1.1.2								X	X		X
FR1.1.3											X
FR1.2.1								X	X		X
FR1.2.2					X	X				X	

Table 3Flat Spring Concept Design Matrix

2.4 EVALUATION OF THE INFORMATION CONTENT PER EACH CONCEPT

Each concept has been compared through second axiom, evaluating its fitting with the accepted range of the given torque. The accepted torque is 50±5Nm,deriving from structural computations.

Different devices employ different technologies and need several working processes in order to be manufactured. The concept which mounts some Belleville springs needs different processes to manufacture the pads joint despite the requested processes for the one that mounts the flat spring. Various machining processes and sequences of these lead different tolerances, dimensional errors, specific features for each kind of manufacturing sequence. It derives these three concepts are intrinsically different and characterized by a different tolerances accuracy. A very important tolerance is the error of critical dimensions because it may influence the values for given torque which may be different than the expected ones. The critical dimension of the flat and helical spring concepts is the radius dimension while the critical dimension of Belleville spring concept is the axial dimension.

Authors will evaluate the matching between the expected range and the response of the system in terms of actuating torque.

The dimensional error has been introduced by machining operations for each concept and it is as known as the characteristic curve which relates that and the torque. The dimensional error is estimated as 0,4mm (i.e. ±2mm) for the critical dimension of the different concepts.

As stated previously, the expected range of torque values depends on dimensional errors which are given by different working processes. The relation which links them is a characteristic curve for each system. In Figure 6 this relation between the given torque and the dimensional error for the flat spring and the helical springs can be seen. The given torque is lower than 50 Nm when the dimensional error tends to increase its value. Positive values are quite acceptable for this application in order to avoid the components overload, so they may not be considered.

In Figure 6 it can be seen how the given torque exponentially increases itself with lower errors when flat springs are used. In such case small variations in error may lead to wide variations in the given torque.

The concept with helical and Belleville springs present a smaller variation of the torque in respect to dimensional error and torque values near the target.

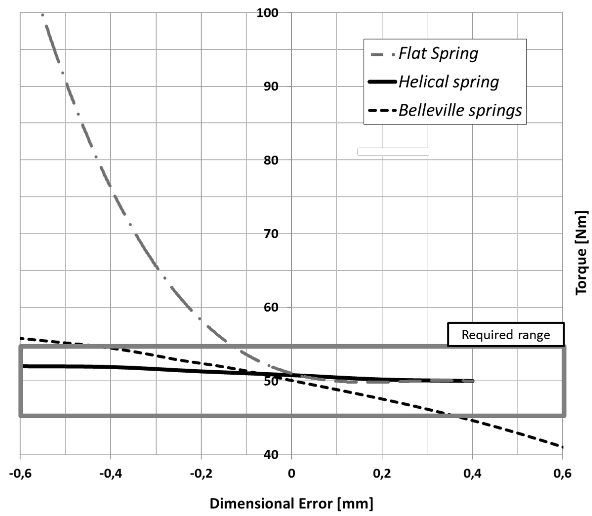

Figure 6 Given torque respect to dimensional error.

The range of dimensional error and its distribution depend on the adopted machining process and their features, which are well known and present in technical datasheets.

The points within dimensional error range are characterized by a probability density function, i.e. a curve giving the specific frequency for each value of them. This curve may be typically a Gaussian but in this paper it has been simplified using a trapezium shaped fuzzy function which is easier to compute.

It is easy to achieve the limits of the range within the given torque falls because of it is dependant by the error through the known relation in Figure 6. The torque frequency values are found in the same way, using those referred to some errors as inputs. In Figure 7 this state is shown concerning the Flat spring concept.

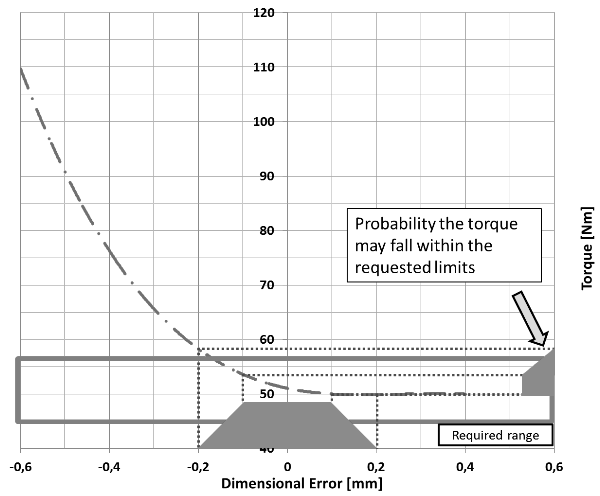

Figure 7 Flat spring response in terms of probability of success.

In Figure 7 the given torque is shown and it falls partially out of expected limits. The information content, i.e. the probability not to satisfy the requested limits, is represented as the area under these curves. In Figure 8 and in Figure 9 the torque distribution in case of helical and Belleville springs is displayed.

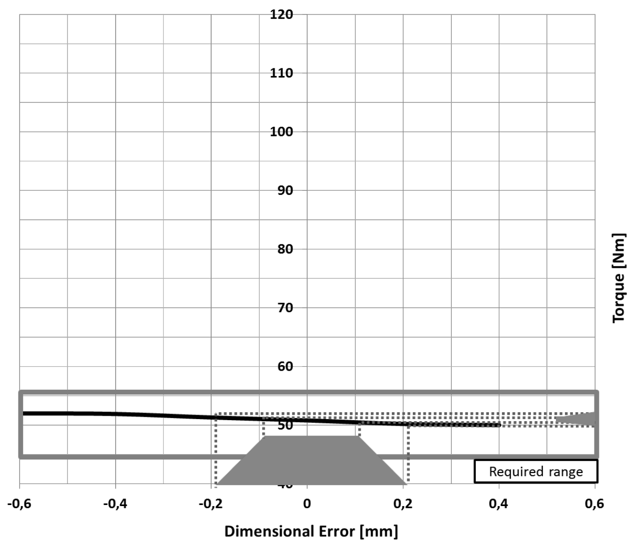

Figure 8 Helical springs response in terms of probability of success.

In Figure 7, 8 and 9 the information content of each of three concepts is shown. It is represented by the area under the torque curve which falls outside the expected limits for torque. In this Helical and Belleville cases this area is collapsed in a narrow strip just inside the expected limits for the torque, so the information content is zero. This achievement is quite foreseeable since the characteristic curve of these springs is very smooth and almost constant, so variations in dimensional error lead to minimal variations for the given torque.

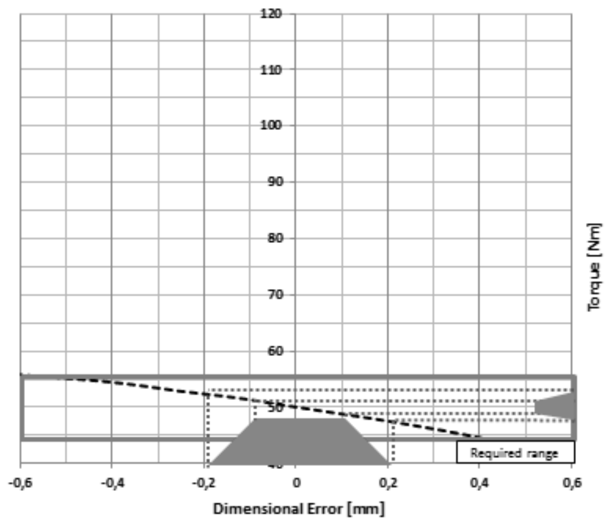

Figure 9 Belleville springs response in terms of probability of success.

3 CONCLUSIONS

In this paper an example of selection among several concepts using axiomatic design is proposed. Three different solutions to achieve the main FR have been presented, so the authors have tried to draw out the design matrix and compare the information content of several concepts in order to select them, according to the two axioms. At first the design matrix for each concept has been drawn. The design matrix of the Belleville Spring concept is the most similar to the ideal one, described in Axiomatic Design Theory. From the point of view of the second axiom, the Belleville spring concept has the lowest information content since the torque distribution falls within the design range. The helical springs concept is the worse from the point of view of matrices comparison but it is characterized by a low information content. The flat spring concepts is not the worse in reproducing the ideal matrix condition, but it has the highest information content since its torque distribution partially falls out of the design range. This leads to identify the best design allowing to dismiss the flat and helical spring concepts.

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