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Optimum Design of Helical Torsion Spring for Fluctuate Loading in Dual Plate Check Valve using MATLAB App Designer

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Abstract

Background: A helical torsion spring is used in the dual plate check valve to open and close the gates. Frequent failure of the helical torsion spring has been identified as an issue in the dual plate check valve within this specific industry. The static design approach is not applicable for designing the spring parameters because the spring is subjected to fluctuating loads due to the sudden opening and closing of the valve gates. Therefore, fluctuating load criteria must be applied to achieve the desired life cycle for the spring. **Methods:** To carry out the fatigue analysis of the spring, this article utilizes an analytical approach where the Modified Goodman Criterion, Spring Index Criterion, Clearance Criterion, and Bending Moment Criterion are employed. The analytical study has been carried out for spring wire diameters ranging from 1 mm to 2 mm to determine the optimum and safe value. **Findings:** A computer program providing a Graphical User Interface (GUI) with the help of MATLAB App Designer has been developed. This program accepts all the design parameters, including the mechanical properties of the spring and the applied external forces. The MATLAB App theoretically computes all the design criteria and identifies the fatigue life of the spring. The findings indicate that a helical torsion spring with a diameter of 1.4 to 1.8 mm is preferable for achieving safe operations for all the design criteria. **Novelty and applications:** This article introduces a novel computer simulation technique based on MATLAB App Designer that generates a Modified Goodman Diagram and performs fatigue analysis for fluctuating stress. The app finally provides the designer with the result about the spring design criteria that can lead to safe operation or failure helping to choose the optimum values of spring parameters.

Keywords: Spring Index; Fluctuate loading design approach; SN curve; Modified GoodMan Diagram; MATLAB App Designer

1 Introduction

For any engineering application requiring the use of a spring, it is essential to identify the appropriate spring configuration. The spring configuration in the application of a check valve depends on the design of the check valve. Hence, for the case study of a dual plate check valve, the helical torsion spring configuration is the most appropriate, since both plates will open due to the regular pressure of the liquid in the pipe, and the plates will close smoothly due to the presence of the spring.

Dual plate check valves are used in industries to achieve regulated unidirectional fluid flow. The functionality of these check valves is achieved with the help of a spring, which is mandatory to close the valve plates. This type of flow regulation is essential in the operation of pumps and compressors, where it acts as a driving standby unit during reverse flow. When backflow of the fluid is restricted, an excessively high surge pressure can occur[1]. Hence, the check valve should be designed in such a manner that it has the capability to withstand the water hammer effect[1]. To restrict the reverse flow velocity to a certain level, it is desired that the valve closes quickly, and rapid fluctuating movements of the plate must be avoided to prevent excessive wear of the moving parts, which could result in early failure of the valve

The dual plate check valve employs two spring-loaded plates hinged on a central hinge pin. When the flow decreases, the plates close due to torsion spring action without requiring reverse flow.

A helical torsion spring is wound at a helix angle about the coil axis. The ends are loaded by a torque, which induces bending as the primary stress in the spring. While designing the dual plate check valve, it is very essential to identify the geometric properties of the spring that will result in higher fatigue life cycles. The usual requirements in the spring design include the appropriate size of spring wire diameter (d), the total stored elastic energy (Ee) in the spring and certain natural frequency of the spring (w).

The spring index is an important property that requires careful analysis when designing a spring. The effects of the spring index have also been studied for the load–displacement response of shape memory spring actuators[2]. Studies even show that the spring used in machinery must have a spring index greater than three[3]. Also, in the case of a helical torsion spring subjected to a torque, the inner diameter changes, leading to a decrease in diametral clearance. Therefore, this parameter also needs to be taken into account while designing the spring[4]. Optimization of a spring for a given spring rate and wire strength can be performed using design formulas provided for linear helical springs with a non-constant wire diameter and with a variable mean spring diameter[5].

A study of the failure causes shows that fatigue failure accounted for a very high proportion, approximately 55%, of all failure forms[6]. Therefore, the design of the spring for a dual plate check valve that must withstand approximately 10^5 cycles needs to be treated as a case of fatigue failure, and a safe fatigue life is to be determined. Fatigue strength criteria are considered in the design of the spring.[7]. The life of any mechanical component subjected to fluctuating stresses is predicted with the help of the Modified Goodman diagram and the S-N curve[8]. In the event of a spring failure in a dual plate check valve application, if we know the maximum force acting on the plates, we can predict the spring's life with the help of the Modified Goodman diagram and the S-N curve[9]. Modified GoodMan diagram is a plot of mean stress vs alternating stress, where a yield line is drawn following to equation $\frac{\sigma_a}{Sy} + \frac{\sigma_m}{Sy} = 1$ and a modified GoodMan line is drawn following to equation as $\frac{\sigma_a}{Se} + \frac{\sigma_m}{Sut} = 1$, where σ_a is alternating stress, σ_m is mean stress, S_{ut} is Ultimate Tensile Strength, S_y is Yield Strength and S_e is Endurance Strength. The effect of mean stress on the fatigue life of the spring has been studied utilizing the Modified Goodman diagram. This diagram determines the safe operating limits under fluctuating loads by considering the alternating stress and mean stress. The failure criterion based on the Modified Goodman diagram has been utilized for coil spring failure and fatigue analysis[10].

Software tools have also been used for designing helical torsion springs using parameters such as torque, material, number of active coils, and required stiffness. An expert system has been developed using software tools like Visual Basic 6.0 and Excel for helical torsion spring design[9]. This can reduce the efforts of a designer in both cases: whether the design is new or involves reusing an existing design with modifications. An expert system is a computer program that uses a knowledge base and inference procedures to solve difficult problems. In its development, software tools like Visual Basic 6.0 and Excel were used. Visual Basic 6.0 software was used for system programming, and Excel was used to store the design data. This kind of expert system can generally be useful for static load studies. A software program was developed using Visual Basic Version 5 to design and analyze springs[3]. A software tool, TURBOMAT-FR, has been developed using MATLAB® scripts to assess the life of turbomachinery fan blades, where the Goodman diagram is used[11]. MATLAB App Designer has been utilized for monitoring various system parameters like speed of the vehicle, battery voltage, current, state of charger etc. of electric vehicle[12].

The literature review suggests that the utilization of software tools with GUI support, specifically for the design of helical torsion springs in dual plate check valves and the identification of fatigue analysis based on S-N curve approaches, has not yet been reported. The work reported here demonstrates the use of MATLAB App Designer, a software tool for predicting the fatigue life of helical torsion springs in the real industrial application of a dual plate check valve as shown in Figure 1. The application developed here helps the designer to provide all the essential information about the spring and load conditions prior to obtaining the results, which include the calculation of all kinds of stresses, plotting the Modified Goodman diagram, and verifying design criteria for fatigue life prediction.

Fig 1. Dual Plate Check Valve with Helical Torsion Spring. The valve used in the problem under study for the industrial application is utilizing single helical torsion spring due to smaller size of the valve. The problem under study is focusing on identifying optimum value of spring diameter that give higher life cycle.

2 Methodology

This section discusses the development of the MATLAB GUI App to help the designer in identifying the optimum helical torsion spring. For achieving higher life cycle in industrial environment, static analysis merely doesn't help too much; rather it is essential to study the behavior of spring under variable stress conditions. In general, the components are subjected to different types of forces like static and fluctuating in such problem under study. Hence fatigue analysis method utilizing SN curve and GoodMan diagram are incorporated in the software developed using MATLAB GUI App.

2.1 MATLAB App Designer

MATLAB offered a Graphical User Interface (GUI) as an option in the past, but now MATLAB recommends App Designer. App Designer supports the creation of applications similar to mobile applications, where users can execute simulations or mathematical problem solutions as standalone programs[(12)]. Since MATLAB App Designer supports user inputs through buttons, numeric fields, text fields, labels, etc., and produces results through graph displays and dialog boxes, such applications can accept a variety of inputs from users and solve problems in the background. Applications developed with this platform provide an interactive feel for the user, making problem-solving much easier due to GUI support. Here, MATLAB App Designer is used as a computational tool for the computation of spring design parameters provided by the user against the fatigue life calculation.

MATLAB App Designer provides a component library from which the designer has to choose the required components as per the application's requirements. Through these components, the designer can handle user input and output activities by placing them on the application layout. Each component's placement, size, and font can be adjusted according to the application's requirements. The overall application design activity is managed through two steps: first, creating a GUI-based application layout that supports the required user input and output functionalities through these components; and second, writing MATLAB code for each of the components placed in the GUI. Each component is visualized as an object within App Designer, and the parameters used within a component can be shared among other components to meet the application's objective.

2.1.1. APP GUI Panel Design

A GUI panel is designed using MATLAB App Designer for the Fatigue Life Analysis of a Helical Torsion Spring for a Dual Plate Check Valve, following the standard fatigue analysis steps. The Spring design parameters are considered like spring wire diameter (d), inner diameter (Di), Pin diameter (Dp), Plate Diameter (Pd) and Number of body turns of the spring (Nb).

All these parameters in the GUI are grouped as per the category and with appropriate label. As shown in Figure 2, the parameters need to be provided as per the units mentioned in the GUI.

The GUI is supported with three Buttons as following.

"COMPUTE": When COMPUTE button shown in Figure 2 is pressed, the application performs analytical calculations and determines the evaluated parameters for moments and stresses as shown in Figure 3. These parameters are used to analyze whether the spring will fail to achieve more than 10^5 life cycles or not.

Input Parameters
Initial force (fi)
final force (fo)
initial torque (T1)
final torque (T2)
No load position angular displacement (theta1)
full load position angular displacement (theta2)
Properties of Material
Modulus of Elasticity (E)
Ultimate Tensile Strength (Sut)
Yield Strength (Sy)
Modulus of rigidity (G)

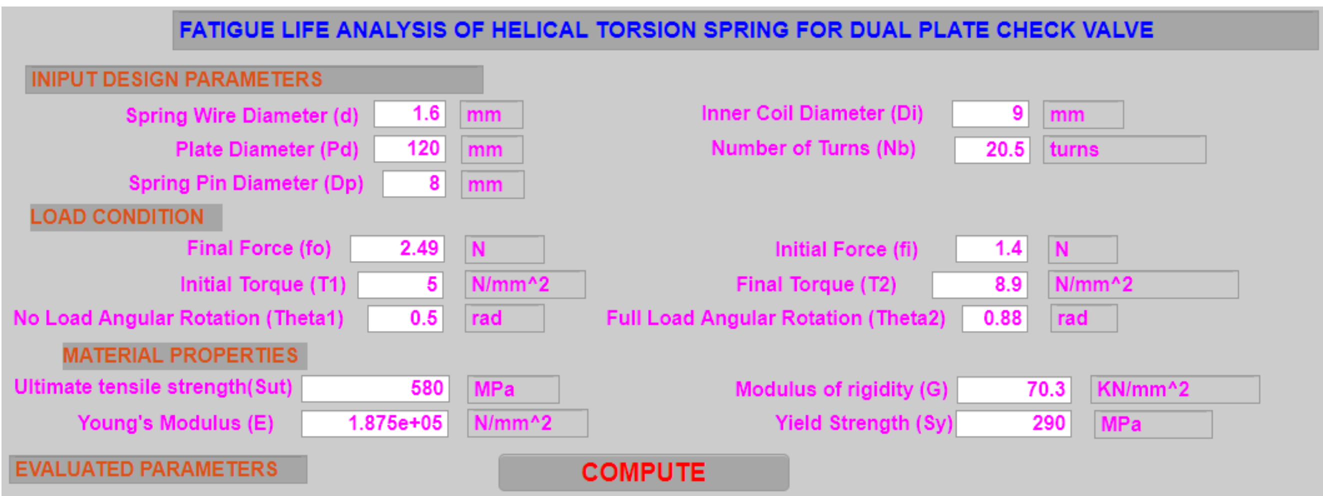

Fig 2. MATLAB App Designer Program Panel for Compute action. The application when started provides this GUI for the user to provide various design parameter as input parameter. When COMPUT button pressed, various parameters are evaluated

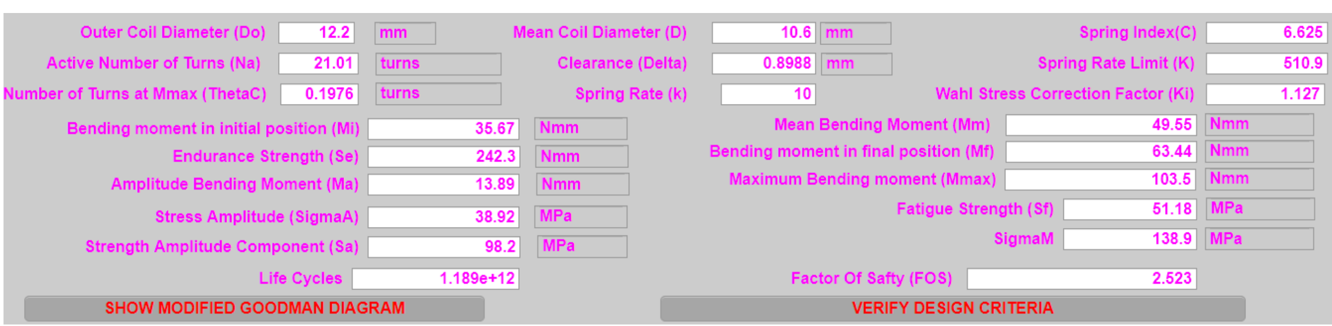

Fig 3. MATLAB App Designer Program Panel for verifying Design Criteria. Once various parameters are evaluated using COMPUT button action, with SHOW MODIFIED GOODMAN DIAGRAM user can visualize the modified Goodman diagram

"SHOW MODIFIED GOODMAN DIAGRAM": When the user interacts with this button, the application generates a Modified Goodman diagram as shown in Figure 4, for further analysis.

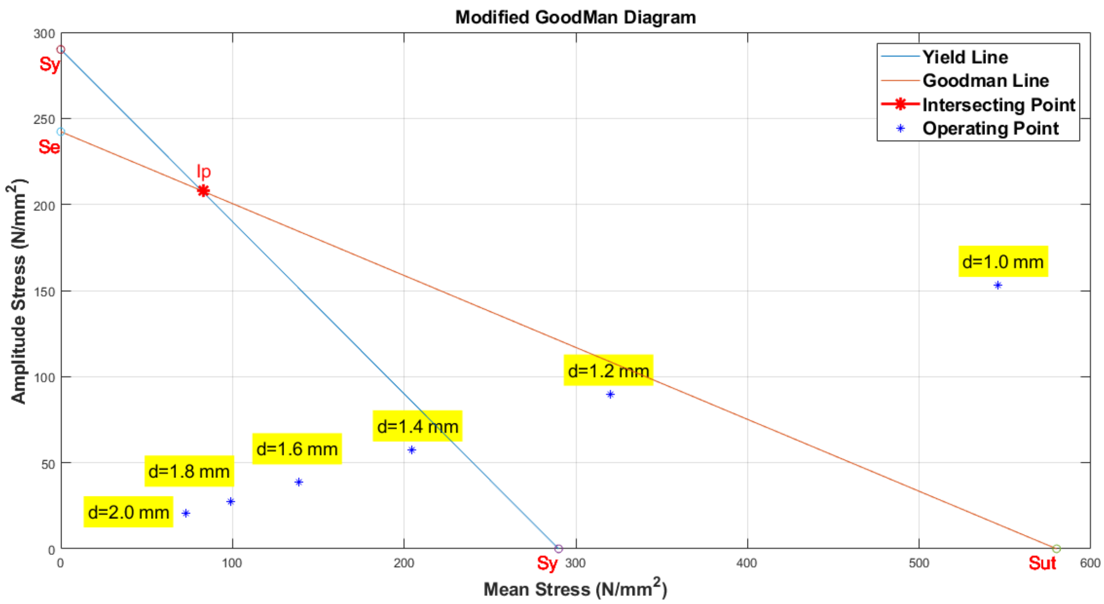

Fig 4. Modified GoodMan Diagram. The plot indicates where the operating point representing amplitude stress and mean stress will be located on Modified GoodMan diagram. Based on the location of this point in specific region, the judgement for failure scenario is derived

"VERIFY DESIGN CRITERIA": The MATLAB App Designer provides an integrated approach to use MATLAB code as per the application requirement. The MATLAB code snippet used in this application for applying the criteria is shown in Figure 5. Using "VERIFY DESIGN CRITERIA" button, the user can verify the spring based on predefined criteria and visualize the result as shown in Figure 6.

```
app.SafeSpringIndexP = 0;
if app.SigmaMP > app.SutP
    app.TextArea.Visible = 'on';
    app.TextArea.Value = 'Spring will fail due to Sut Limit cross';

elseif app.SigmaMP < app.SutP
      check for Clearance criteria
    if app.deltaP > 0.1*app.DaP
        check for spring index criteria
        app.Spring_Index_Limit_L = (app.CP - 6.0) + 0.001;%+ve
        app.Spring_Index_Limit_H = (12 - app.CP) - 0.001;%+ve

        str_e = sprintf('Spring_Index_Limit_L = %0.2f,Spring_Index_Limit_H = %0.2f ',app.Spring_Index_Limit_L,app.Spring_Index_Limit_H);
        if (app.Spring_Index_Limit_L > 0 && app.Spring_Index_Limit_L > 0)
            app.SafeSpringIndexP = 1;
        else
            app.TextArea.Visible = 'on';
            app.TextArea.Value = 'Spring will fail due to Spring Index Limit';
        end
    elseif app.deltaP < 0.1*app.DaP
        app.TextArea.Visible = 'on';
        app.TextArea.Value = 'Spring will fail due to clearance';
    end
end
```

Fig 5. MATLAB App Designer Code snippet for the Verify Design Criteria

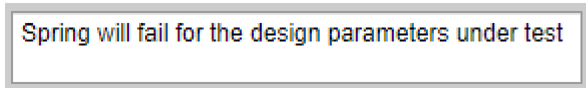

Fig 6. MATLAB App Designer Program Panel for verifying Design Criteria results. Once VERIFY DESIGN CRITERIA button is pressed, user will get the result, whether the spring with provided parameters will fail to achieve more than 10^5 cycles during the application or remain safe

2.1.2. MATLAB Code Implementation

MATLAB App Designer provides support for code implementation alongside the Design View. This allows various mathematical and logical operations to be performed on the parameters entered via the GUI Panel. For each button component, an individual callback function is prepared, containing the MATLAB code for performing the necessary computational activity as per the App's requirements. It is required to compute the following parameters based on the entry of essential parameters such as spring wire dimensions, its material properties, and the load condition. Following a callback for the "COMPUTE" button, various parameters like moments and stresses are evaluated. These are necessary to prepare a Modified Goodman Diagram, which is based on the material properties such as Ultimate Tensile Strength (S_{ut}), Yield Strength (S_y), and Endurance Strength (S_e). This diagram, drawn as Amplitude Stress versus Mean Stress, essentially helps in identifying the Fatigue Strength (S_f) and Life Cycle of the spring under defined load conditions.

To achieve the functionality associated with all three buttons, an individual callback function is prepared for each button with the help of the necessary MATLAB code. The evaluated parameters from the COMPUTE callback are utilized for preparing the Modified Goodman diagram, in which the Yield Line and Modified Goodman Line are drawn on Amplitude Stress (σ_a) versus Mean Stress (σ_m) curve, as shown in Figure 4.

Yield Line is a line that connects Sy on both the axis and represented as $\frac{\sigma_a}{Sy} + \frac{\sigma_m}{Sy} = 1$. GoodMan line is a line that connects Sut and Se on Mean Stress axis and Amplitude Stress axis respectively and represented as $\frac{\sigma_a}{Se} + \frac{\sigma_m}{Sut} = 1$.

The plotting functionalities in the MATLAB code are utilized in the "SHOW MODIFIED GOODMAN DIAGRAM" callback to plot the Yield line, Goodman line, their intersection point, and the point representing the Mean and Amplitude stress. The intersecting point, along with Sy and Se helps in identifying the regions on this plot as a safe region, within which if the operating point lies, then it will theoretically lead to an infinite life cycle. The callback related to the "VERIFY DESIGN CRITERIA" button identifies this region and shows the result as to whether the spring will fail or not, along with the criterion reason for the failure, in the following manner.

2.2 Optimum Design Criteria Identification

To identify the spring failure based on the evaluated parameters, following criteria are identified.

- Modified GoodMan Criterion
- Spring Index Criterion
- Clearance Criterion
- Bending Moment Criterion

2.2.1. Modified GoodMan Criterion

The Modified Goodman diagram is employed to evaluate the fatigue life of a spring subjected to a combination of mean and alternating stresses in scenarios involving cyclic loading. Amplitude Stress and Mean Stress are important parameters for evaluating whether the spring will deform under applied stress conditions. If a design parameter's mean stress exceeds the Ultimate Tensile Strength, it will result in spring failure. In Figure 4, the region on this diagram below the Goodman line, representing Mean Stress under the Ultimate Tensile Strength (S_{ut}), is considered a safe region. However, within this region, there is a significant sub-region identified by the 'S_y-I_p-S_{ut}' triangle, which denotes the effects of plastic deformation. This sub-region should be excluded and considered as a failure zone in the case of fluctuating loading. When the Mean Stress value starts crossing the Yield Strength (S_y), plastic deformation begins. Hence, it is required that the condition $\sigma_m < S_y < S_{ut}$ and $S_f < S_e$, is met where S_f is the fatigue strength and it is referred as the maximum alternating stress a spring can withstand for a given number of cycles without failure. As an important design criterion to avoid fatigue failure, it is required to identify, whether the operating point representing Amplitude Stress and Mean Stress lies in the safe region or not.

2.2.2. Spring Index Criterion

Variations in the spring index, which is the ratio of the mean coil diameter to the wire diameter (D/d), influence the performance of the spring. The spring index in a helical torsion spring is an indicator of the stress level that the spring can bear and, hence, is a key factor in defining one of the criteria to judge if the spring fails or not.

Springs with a lower spring index are less flexible because the coils are tightly wound. A lower spring index leads to the generation of higher stresses at points along the wire surface, especially at localized points, resulting in spring failure and a shortened fatigue life. Manufacturability is also a major concern with lower spring index values. On the other hand, springs with a higher spring index are more flexible but have a lower load-bearing capacity. Buckling is more readily observed as the load increases in these springs. A balance between flexibility and strength can be achieved with an appropriate value of the spring index. The range for the spring index usually referred to in the literature for helical torsion springs is between 6 and 12, and hence, the same criterion is used in the MATLAB App Design.

2.2.3. Clearance and Bending Moment Criterion

During the application of maximum force on the dual plate of the check valve, the spring winds in the inner direction, due to which the distance between the spring's inner surface and the pin reduces. The clearance representing this distance is calculated based on $\Delta = \left(\frac{N_b{}^*D}{N_b+\theta_c}\right) - d - D_p$, where N_b is Number of Body Coils, θ_c is the Number of turns of the coil body at M_{max}, D_p is Pin diameter and D is Mean Coil Diameter. The clearance criterion followed is $\Delta > 0.1 * D_p$.

For the bending moment, it is essential to observe the value of Maximum Bending Moment (M_{max}) which can be computed using $M_{max} = \frac{\pi d^3 S_y}{32^* K_i}$, against the bending moment in final position (M_f) which is computed by using $M_f = F_o{}^* L$. A criterion for the bending moment, which is required to be fulfilled for the required fatigue life of the helical torsion spring, is $M_{max} > M_f$.

2.2.4. Life Cycle Calculation

Once Modified Goodman diagram is obtained, it can be predicted whether the spring component will be safe or not based on fatigue strength S_f, calculated with formula $S_f = \frac{\sigma_a S_{ut}}{S_{ut-}\sigma_m}$. It is required to find out the location of point(σ_m, σ_a) in the Modified Goodman diagram and need to investigate whether it is lying in the safe zone or not. For calculating life cycles further, S-N curve is required where both the axis are plotted with log-log values. For the calculated value of the fatigue strength S_f, it is required to find out the life cycle from Figure 7.

3 Result and Discussion

The application, developed with the help of MATLAB App Designer, is utilized for the fatigue analysis of helical torsion springs where Stainless Steel material with grade 316 is selected. It is the spring diameter that is crucial for identifying a spring with fail-safe operation. Hence, with the help of the application, spring index, clearance, and various stress parameters are computed individually for all the springs with diameters in the range of 1 mm to 2 mm. A Modified Goodman diagram is generated where an operating point, representing the mean and amplitude stress values for each wire diameter, is plotted. The location of the operating point helps in summarizing the fail-safe operation associated with the spring diameter in the context of the fail-safe regions on the Goodman diagram as one of the criteria. Table 1 shows the Fatigue Life Prediction based on Spring Wire Diameter following all the four criteria.

Figure 8 shows the Fatigue Life Prediction based on spring wire diameter (d) in the range of 1 mm to 2 mm. The fatigue life of the spring should not be judged only based on the theoretical values of the life cycle. The spring is safe only if all four criteria discussed in Section 3 are successfully met. As a first criterion to verify the region in which the operating point, representing Mean and Amplitude Stress, is located, for spring wire diameters in the range of 1.4 mm to 2.0 mm, it is found in the safe region, as described in Figure 4.

Following the spring index criterion for 'C' in the range of 6 to 12, the spring with a wire diameter of 2.0 mm fails, while other springs with 1.4, 1.6, and 1.8 mm wire diameters follow the spring index criterion as well as the clearance criterion $\left(\Delta > 0.1 * D_p\right)$ as the pin diameter $\left(D_p\right)$ is 8 mm. Figure 9 shows the Graphical representation of effects of Spring Wire Diameter on Spring Index and Bending Moment. The Bending moment in final position (M_f), is 63.44 Nmm and it is compared with the Maximum Bending Moment (M_{max}). This criterion is also followed, and hence, the springs with wire diameters in the range of 1.4 mm to 1.8 mm remain safe. For the spring with a wire diameter 'd' of 1.0 mm, the operating point lies outside the Goodman line and hence fails, even though the Spring index and Delta criteria are met. For the spring with a wire diameter 'd' of 1.2 mm, the operating point lies in the region represented by the 'S_y-I_p-S_{ut}' triangle in Figure 4, which is the region where

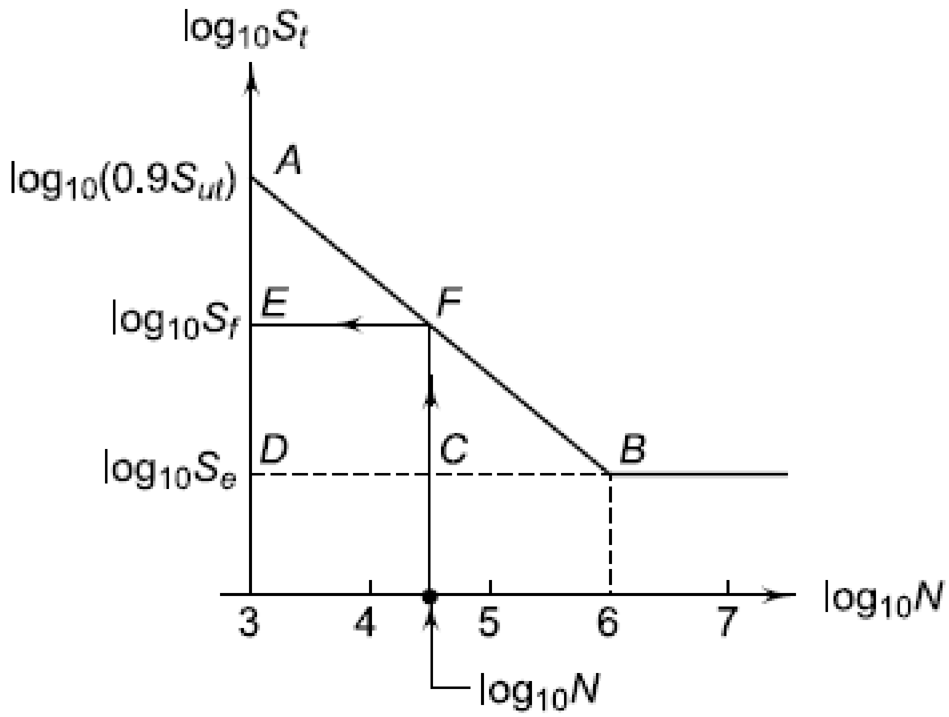

Fig 7. Reference graph for Life Cycle Calculation using S-N Curve. After calculating Sf, the SN curve is used to compute the life cycle (N) Source: Bhandari, V. B. (2020). Design of Machine Elements (5th ed.). McGraw Hill Education India Private Limited.

plastic deformation in the spring wire starts to be observed, ultimately considered a failure case. For the cases of spring wire diameters 'd' of 1 mm and 1.2 mm, the Bending Moment criterion is also not fulfilled.

Table 1. Fatigue Life Prediction based on Spring Wire Diameter

Wire Dia. (mm)	Theoretical Life Cycles	Spring Index (C)	Delta (∆)	Maximum Bending MomentM_{max}(Nmm)	Fatigue Life
1.0	S_f –ve	10.00	0.85	26.33	FAIL
1.2	1.10E + 3	8.50	0.872	44.86	FAIL
1.4	5.10E + 6	7.42	0.887	70.26	SAFE
1.6	2.20E + 10	6.62	0.898	103.5	SAFE
1.8	1.50E + 12	6.00	0.907	145.4	SAFE
2.0	1.10E + 13	5.50	0.914	196.8	FAIL

4 Conclusion

The MATLAB GUI-based application designed here for the verification of helical torsion spring parameters in a dual plate check valve is novel in itself, providing utility for the designer not only to verify spring parameters against fatigue life but also to select specific design parameters like spring wire diameter and spring index. In the absence of such tool, it is usually required to follow mathematical steps to perform all the necessary calculations for various parameters like mean stress, amplitude stress, bending moment, clearance, and spring index for the selected spring wire diameter. The support of a GUI within the application presented here helps in handling the input parameters in a user-friendly manner when the designer wants to generate the computational results and plot the Modified Goodman diagram. The Modified Goodman criterion, Spring Index criterion, Clearance criterion, and Bending Moment criterion are used following theoretical analysis in predicting the fail-safe operation associated with the spring for a given spring wire diameter. This application helps the designer to quickly identify the appropriate

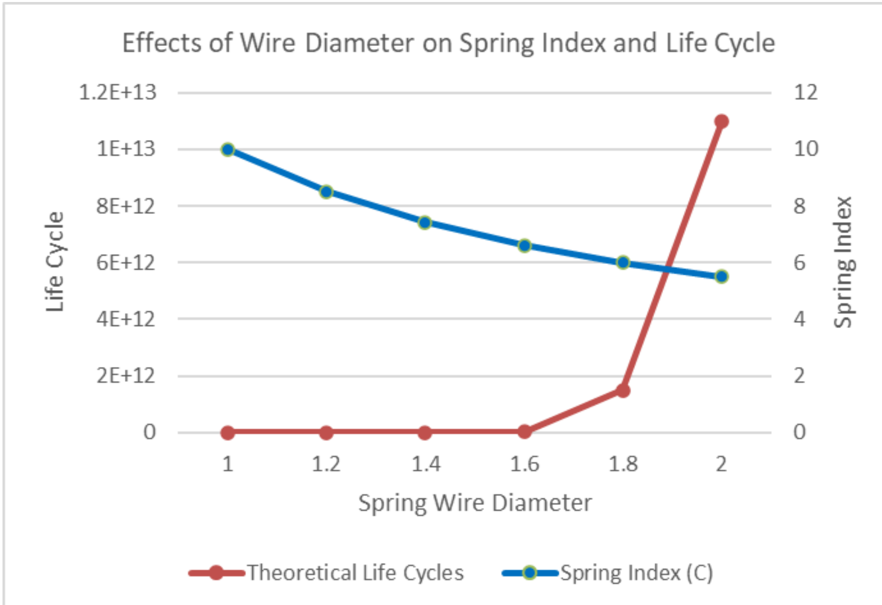

Fig 8. Effects of Spring Wire Diameter on Spring Index and Life Cycles

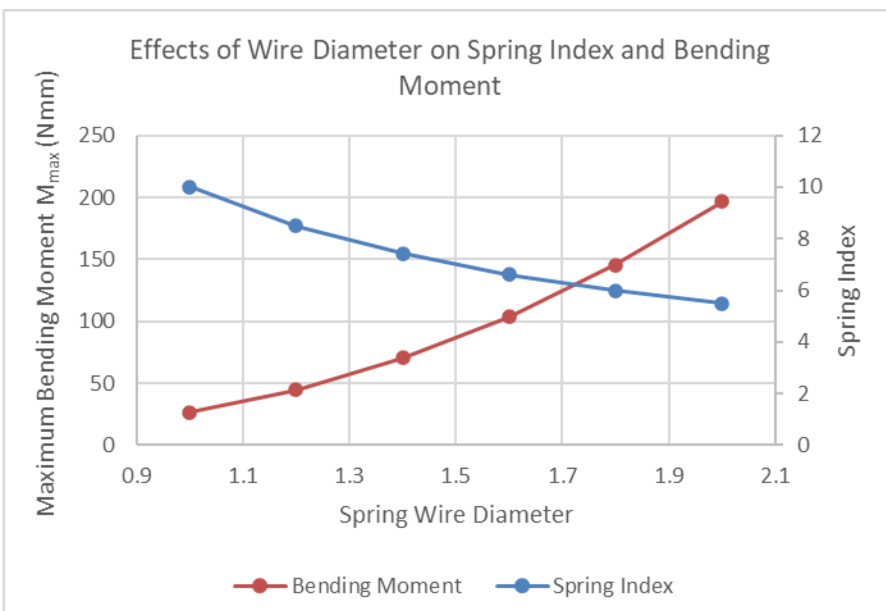

Fig 9. Effects of Spring Wire Diameter on Spring Index and Bending Moment

wire diameter for the helical torsion spring in a dual plate check valve. The use case represented here for a helical torsion spring in a dual plate check valve suggests that springs with wire diameters of 1.4 mm, 1.6 mm, and 1.8 mm indicate safe working conditions, while other options lead to spring failure. This indicates that optimum value of the wire diameter for this application is in the range of 1.4 mm to 1.8 mm, where the criterion regarding Modified Goodman, Spring Index, Clearance, and Bending Moment are followed successfully.

The use of MATLAB App Designer presented here is applicable to all the industrial problems where helical torsion spring is used. The type of fluctuating stresses required to be considered in such applications are incorporated in the design steps of this application. Hence the approach presented here can be applicable to any such industrial problem.

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