DINAME 2023 - Proceedings of the XIX International Symposium on Dynamic Problems of Mechanics,
A.S. De Paula, A.T. Fabro and M.R. Machado (Editors), ABCM.
Pirenópolis, Go, Brazil, February 26th to March 3rd, 2023

Fatigue based topology optimization of metallic flexible disc coupling

Gabriel Dantas Gomes[1], **Felipe Wenzel da Silva Tuckmantel**[1] **and Katia Lucchesi Cavalca**[1]

[1] Universidade Estadual de Campinas, Rua Mendeleyev, 200

Abstract: Misalignment in rotating machinery is a frequent event, being considered the second most prevailing cause of failure after unbalance. The types of misalignment can be axial, parallel, angular or a sum of these. Flexible disc coupling works as a mean to transfer torque while reducing restitution moment generated by small misalignment between coupled parts. Although many advanced techniques are available to apply a precise alignment between shafts, every machine has some degree of misalignment. When under misalignment, flexible coupling generates restitution forces and moments which are introduced into the system, thus causing additional vibration. The goal of this work is to perform a topology optimization, with aid of Finite Element Method, on a circular disc coupling to achieve minimum restitution moment under angular misalignment while maintaining fatigue life safety factor similar to the original disc, as it is well known that with minimal moment the additional vibration caused by misalignment will also be smaller when compared to original circular disc. The component will be on linear elastic region. With minimal moment the additional vibration caused by angular misalignment will also be smaller when compared to original circular disc. Simulation results indicate optimized discs shapes have a restitution moment sixty percent lower, safety factor almost two times higher and lower tensions when compared to original circular disc.

Keywords: Flexible disc coupling, Angular misalignment, Topology optimization

INTRODUCTION

Mechanical couplings are machine elements widely used to transfer energy between two shafts linked by their ends. Its main function is to connect two rotating elements, while allowing some misalignment. Almost every rotating machinery has a coupling in its structure to assure an adequate operation. As a perfect alignment is near impossible to achieve, every coupling will have some degree of misalignment, thus introducing a restitution moment into the system, which results in greater vibration amplitudes and harmonic components which could lead to superharmonic resonances under specific operation conditions.

The number one cause of failure in rotating machinery is unbalance followed by misalignment in shafts (Muszynska, 2005; Patel; Darpe, 2009). Misalignment is estimated to be responsible for more than 70% of vibration problems like premature failure of bearings, shaft fracture, noise and excessive vibration (Bognatz, 1995).

Since there is no literature analysis correlating misaligned disc coupling geometry with restitution moment and fatigue life, its optimal shape under such circumstances is unknown. As discs might not be in their most efficient layout, the dynamic effect caused by them in the mechanical system is possibly bigger than it could be, causing unnecessary wear. Dynamic analysis of disc coupling optimal geometry, through Topology Optimization (TO), would bring light into a problem which has few available information and of potential impact on machine lifespan.

The goal of this work is to find optimal geometry of a flexible disc coupling, as suggested by (Tuckmantel, 2018). This will be carried out through TO, with aid of Tosca software, in a way that restitution moment generated by disc bending will be lowest possible for a 0,5° angular misalignment. Fatigue life and safety factor (SF) will be higher or equal than values for original circular disc. Finite Element Method (FEM) along with TO and fatigue infinite life design will be used to obtain desired results. The proposed approach uses elasticity theory to describe disc behavior, which is modeled as thin shell and considers the material to be linear, elastic and isotropic (Tuckmantel and Cavalca, 2019), (Tuckmantel et al., 2020).

THEORETICAL MODEL

During initial machine assembly there is some degree of misalignment, which can further increase during operation due to foundation movements, thermal expansion and other factors. To minimize this unwanted effect, flexible coupling add misalignment allowance capacity (Mancuso, 1999). Misalignment is a condition in which coupled shafts center lines are not colinear (Xu and Marangoni, 1994), and three types of this setting are: axial, parallel, angular and a combination of at least two of these. The most common types of metallic disc couplings are: circular, hex, segmented, scalloped. According to Mancuso (1999), the circular shape, which is the most easily produced, is the least employed due to force line tendency to straighten curved segment, generating higher traction and compression tension.

FEM allows the calculation of parameters like stress and strain of complex mechanical system, through discretization and numerical solution of differential equation. The general procedure of this method is to divide a continuous structure into discrete counterparts, applying material physical properties, boundary conditions, loading and solve the system of equations to determine nodal displacement. The most used element type for plane stress is the quadrilateral type, due to its higher convergence rate when compared to triangular type. The disadvantage of quadrilateral element is lower precision if element distortion occurs in the initial undeformed state (Cook, 1995; Fish and Belytschko, 2007). Discretization of metallic disc coupling in Abaqus software uses the thin shell elements, which are quadrilateral with four nodes, six degrees of freedom per node and reduced integration (S4R). Inertial and nonlinear geometry effects are included in nodal displacement calculation.

The TO of a structure greatly impacts its performance. Bendsoe and Kikuchi (1988) developed a material distribution method to generate optimal geometry of structures, through the definition of shape in terms of material density. In structures with thin thickness, when compared to its other dimensions, the material distribution method predicts truss and grid like shapes Bendsoe and Sigmund (2003).

Fatigue is sudden and unexpected failure, most of the time, that occurs in structures and equipment subject to cyclic loading. According to Stephens et al. (2000), at least 50% of all mechanical failures are caused by fatigue and most are unforeseen. For infinite life fatigue design, the safety factor can be calculated in the Goodman modified diagram. In multiaxial fatigue a Critical Plane Analysis, adapted from Brown and Miller (1973), is implemented in fatigue analysis software fe-safe to determine the stress state, given by Eq. 1. The parameters in this equation are: γ shear strain, ε_n normal strain, $\sigma_f^{'}$ fatigue resistance coefficient, N_f number of cycles, b Basquin fatigue resistance exponent, $\varepsilon_f^{'}$ fatigue ductility coefficient and c Coffin-Mason ductility exponent. These values are determined from the characteristic SN curve of the material.

$$\frac{\Delta\gamma}{2} + \frac{\Delta\varepsilon_n}{2} = 1,665\frac{\sigma_f^{'}}{E}(2N_f)^b + 1,75\varepsilon_f^{'}(2N_f)^c \qquad (1)$$

In order to achieve the optimal disc coupling geometry a commercial circular disc made of 301 steel and 1/8 hard will be modeled by FEM, an angular misalignment is applied and restitution moments and stress are calculated. Based on stress state results from the previous static analysis, a TO is accomplished to find the best shape that minimizes restitution moment, through strain energy maximization with decreasing volume as restraint. Obtained optimized disc geometries are used to perform dynamic analysis under angular misalignment, which then calculates the fatigue safety factors for each shape. The final optimized geometry has higher safety factor, reliability and introduces lower restitution moment into the system, leading to reduced failure rates.

RESULTS AND DISCUSSION

To calculate disc coupling stress and reaction moment generated by 0,5° angular misalignment, static and dynamic analysis are performed in Abaqus. First, an angular misalignment is applied through a reference point with kinematic coupling on the two holes of driving shaft, while the driven part is restrained on all its six degrees of freedom by another reference point. This is done with a single static step analysis. The number of elements in a mesh is defined by a convergence analysis, partitioning the disc surface area in different regions, reducing the element size and comparing differences in stress values. The final mesh is finer at the holes adjacency, due to higher stress gradient in this location, and coarser on the rest of the disc, as shown in Fig. 1, with 29250 elements, hole elements size of $5x10^{-5}$ m and remaining elements size of $3x10^{-4}$ m.

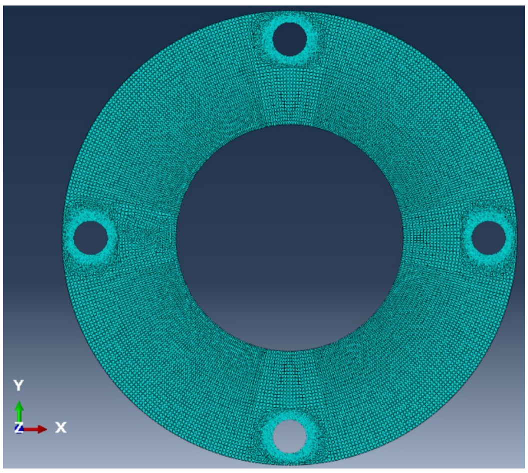


Figure 1: Circular disc with adequate mesh.

A dynamic analysis is necessary to include inertial effects of the disc. In this case, the same mesh is also applied. A concentrated moment, obtained in previous static analysis as a reaction moment, replaces angular misalignment around X axis, a rotation velocity of 70 Hz around Z axis is applied to the driving holes and rotational degrees of freedom X,Y and displacement degree Z are restrained from movement in the driven holes. This analysis is done with two steps: first a static step with conditions similar to the static analysis previously done, and then a dynamic implicit step. In the second step, the rotational velocity and concentrated moment are applied and the only restrained degrees of freedom are rotational X and Y in driven shaft. Those two steps analysis increase convergence rate and reduce simulation execution time because the misalignment is static applied, and then internal effects take place in the second step. The method of solution for the dynamic analysis is Hilber-Hughes-Taylor, according to Hilber et al. (1977), with moderate dissipation and parameters α = -0,41421, β = 0,5 and γ = 0,91421.

Safety factor for infinite life design is calculated with stress results from dynamic analysis, which are transferred from Abaqus to fe-safe. The load is applied through stress tensors obtained with time integration, with initial time of 0,00139s, after a quarter of rotation to exclude start up effect, and final time of 0,0156s, after a single full revolution to simulate one fatigue cycle. Environment temperature considered was 20°C, and correction factors are applied in Brown-Miller method. Final results from fe-safe for the circular disc are shown in Fig. 2, and are the baseline for the optimized disc shape. The location with lower safety factor is near the hole region, as expected, with value of 1,076.

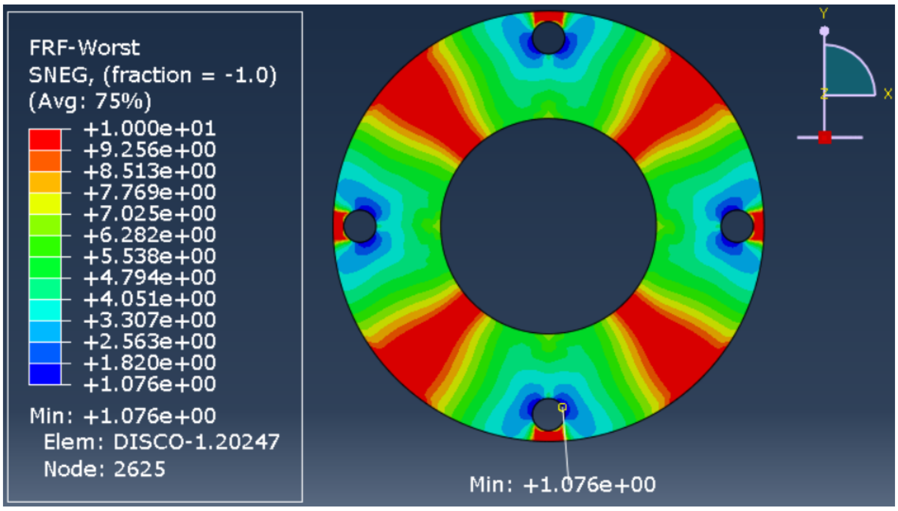
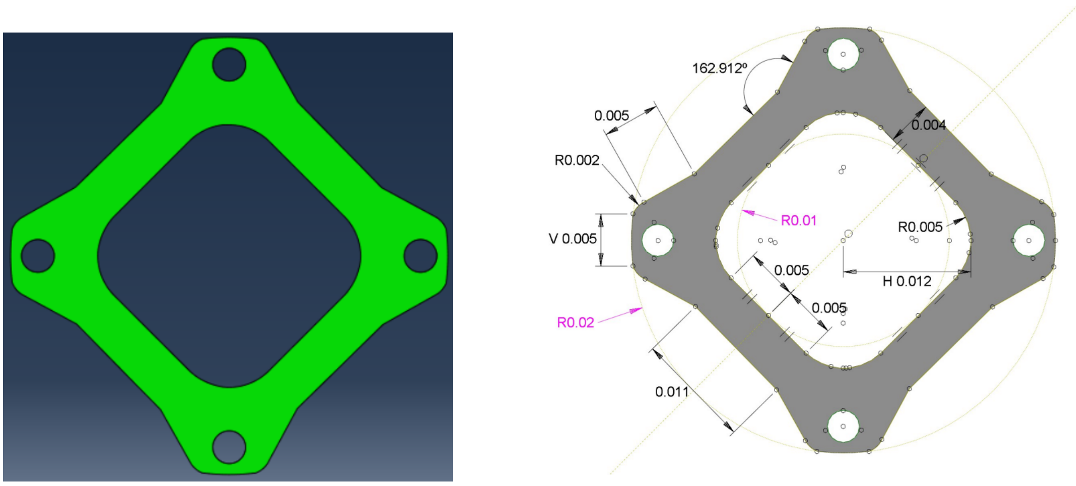


Figure 2: Infinite life fatigue safety factor in circular disc.

With results from static analysis the TO is performed in Tosca software on circular disc. The approach must maximize objective function strain energy, to reduce structural stiffness, thus, reducing restitution moment. The applied restrictions are: total disc volume and rotational symmetry. When optimization is based on dynamic analysis and safety factors the simulation time increases exponentially, which precludes its execution. It is important to emphasize this procedure would lead to most accurate results, since it optimizes the parameters of interest directly, and not on indirect properties which are proportionally correlated with the former. From original circular disc with 301 steel 1/8 hard, excluding hole regions from design domain and reducing final volume by decrements of 10% until reaching 40%, the results are shown in Tab. 1. Based on safety factor, restitution moment, reliability values and manufacturability, the model V_f = 50% V_0 is selected as the best combination of final parameters. Its geometry and dimensions are presented in Fig. 3.

Table 1: Safety factor, reliability and restitution moments in optimized discs.

Final Volume [% V_0]	Safety factor	Reliability [%]	Restitution moment [Nm]	Reduction of moment [%]
100	1,076	34,96	0,159702	0,00
90	1,171	67,67	0,152997	4,20
80	1,187	71,64	0,139594	12,59
70	1,267	86,03	0,124732	21,90
60	1,556	99,36	0,100781	36,89
50	1,662	99,82	0,0894269	44,00
40	2,059	99,99	0,0640771	59,88



(a) (b)

Figure 3: Optimized disc with V_f= 50% V_0: (a) geometry and (b) dimensions.

CONCLUSION

The achieved results were satisfactory and when compared to available disc couplings geometries offered by suppliers, they are very similar to scalloped shape. This indicates analyses are correct and further improvement in disc shape is possible to reduce restitution vibration. An experimental test would further confirm this.

ACKNOWLEDGMENTS

This study was supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – Finance Code 001 - and CNPq #163804/2021-4, #307941/2019-1.

REFERENCES

Bendsoe, M. P., Kikuchi, N., 1988, “Generating optimal topologies in structural design using a homogenization method”, Computer Methods in Applied Mechanics and Engineering, v. 71, n. 2, p. 197–224.

Bendsoe, M. P.; Sigmund, O. L. E., 2003, “Topology Optimization: Theory, Methods, and Applications”, Ed Springer.

Brown, M. W.; Miller, K. J., 1973, “A Theory for Fatigue Failure under Multiaxial Stress-Strain Conditions”, Proceedings of the Institution of Mechanical Engineers, v. 187, n. 1, p. 745–755.

Bognatz, S., 1995, “Alignment of critical and non critical machines”, p. 23–25.

Cook, R. D., 1995, “Finite Element Modeling for Stress Analysis”, Ed Wiley.

Fish, J.; Belytschko, T., 2007, “A First Course in Finite Elements” Ed John Wiley.

Hilber, H. M.; Hughes, T. J. R.; Taylor, R. L., 1977, “Improved numerical dissipation for time integration algorithms in structural dynamics”, Earthquake Engineering & Structural Dynamics, v. 5, n. 3, p. 283–292.

Mancuso, J. R., 1999, “Couplings and Joints: Design, Selection & Application”, Ed CRC Press.

Muszynska, A., 2005, “Rotordynamics”, Ed CRC Press.

Patel, H.; A. Darpe, 2009, “Vibration response of misaligned rotors”, J. Sound Vibr. 325, p.609–628.

Stephens, R. I.; Fatemi, A.; Stephens, R. R.; Fuchs, H. O., 2000, “Metal Fatigue in Engineering”, Ed John Wiley & Sons.

Tuckmantel, F. W. d. S., 2018, “Análise de modelo numérico de acoplamento de disco flexível”, Tese (Doutor em Engenharia Mecânica) — Universidade Estadual de Campinas.

Tuckmantel, F. W. d. S., Cavalca, K. L., 2019, “Vibration signatures of a rotor-coupling-bearing system under angular misalignment”, Mechanism and Machine Theory, v. 133, p. 559–583

Tuckmantel, F. W. S.; Castro, H. F.; Cavalca, K. L., 2020, “Investigation on Vibration Response for Misaligned Rotor-Bearing-Flexible Disc Coupling System—Theory and Experiment”, Journal of Vibration and Acoustics, v. 142, n. 2

Xu, M.; Marangoni, R. D., 1994, “Vibration Analysis Of A Motor-Flexible Coupling-Rotor System Subject To Misalignment And Unbalance, Part I: Theoretical Model And Analysis”, Journal of Sound and Vibration, v. 176, n. 5, p. 663–679.

RESPONSIBILITY NOTICE