Scientific Research Publishing

Modern Mechanical Engineering, 2024, 14, 51-56
https://www.scirp.org/journal/mme
ISSN Online: 2164-0181
ISSN Print: 2164-0165

FEA-Based Fatigue Life Assessment of Cycloidal Displacement Cam and Flat-Faced Follower Mechanism

Shengyong Zhang, Krishnajith Theril

Department of Mechanical and Civil Engineering, College of Engineering and Sciences, Purdue University Northwest, Hammond, USA
Email: syzhang@pnw.edu

How to cite this paper: Zhang, S. and Theril, K. (2024) FEA-Based Fatigue Life Assessment of Cycloidal Displacement Cam and Flat-Faced Follower Mechanism. *Modern Mechanical Engineering*, **14**, 51-56.
https://doi.org/10.4236/mme.2024.142005

Received: April 8, 2024
Accepted: May 24, 2024
Published: May 27, 2024

Abstract

Cam-followers provide reliable and controlled motions in various mechanical systems. Due to the highly fluctuating load between the cam and follower in operation, the cam-follower may be subjected to a high risk of contact fatigue failure. This paper assesses the fatigue life of a cycloidal displacement cam and a flat-faced follower under the defined loads and constraints. Computer-aided design (CAD) model of the cam-follower is developed in CATIA software and imported to ANSYS software for finite element analysis (FEA) of fatigue life. MATLAB programming is developed for determining the appropriate spring constant and pre-load force to always keep the cam and follower in contact. The fatigue life of the cam-follower has been estimated under the specified operating conditions. The analysis method can be applied to investigate the fatigue life of cams with other profiles, including the modified trapezoidal functions, polynomial functions, etc.

Keywords

Cam-Follower, CAD, FEA, Fatigue Life

1. Introduction

Cam-follower systems are frequently used in all kinds of machines. The cam-follower is an extremely useful device, without which the machine designer's tasks would be more difficult to accomplish [1]. Due to the highly repeated or fluctuating load between the cam and follower in operation, the cam-follower may fail due to fluctuating stress, which is well below the material's ultimate stress, and quite frequently even below the yield stress. Compared to static failure with a visible warning in advance, fatigue failure of a cam-follower gives no warning and is hence dangerous. It is necessary to estimate the fatigue life in the design of cam-follower systems.

Jayakumar, Aldrin and Somesh [2] conducted a theoretical study on the normal compressive force between the cam and the follower for various cam rotational angles. The Hertz contact stress and surface wear were calculated based on the above obtained compressive force. FEA-based simulations were conducted at the cam nose region, cam tangent region, and cam base circle region for validation. It was suggested that a relatively smaller pressure angle was preferred for good function of the internal combustion engine valve train system, provided that the pressure angle and the cam angle were the criteria for the wear design of the cam and follower mating. Tesfie [3] analyzed the wear of the cam and follower contact with respect to the cam angle and the pressure angle. It was concluded that the contact pressure, von Mises stress, and surface wear increased with the cam rotational angle. Jamali *et al.* [4] presented a numerical study for the cam and flat-faced follower lubrication by dealing with the cam-follower contact as an electrohydrodynamic lubrication (EHL) point contact problem. The impact on the film thickness, pressure distribution, and surface deformation was investigated by considering the different forms of axial cam surface geometry, variation of applied load, and cam rotational speed. The reduced surface deformation was expected to subsequently affect the level of stress and fatigue life of the system. Vardaan and Kumar [5] built the CAD model of a disc-type cam and spherical follower used in typical internal combustion engines. Structural steel and grey cast iron were compared in the FEA analysis for the contact pressure and Hertz contact stress. It was concluded that the maximum values of both contact pressure and Hertz contact stress were lower for grey cast iron material, which was preferred for fabricating the cam and follower pair of a motorcycle internal combustion engine. Patil, Patil, and Karuppanan [6] conducted FEA modal and fatigue analyses of a camshaft to investigate the natural frequency, mode shapes, and fatigue alternative stresses. The analysis results were compared with Dunkerley's method and fatigue life theories (Goodman, Soderberg, and Gerber) for validation. The results showed that the natural frequency was fairly far away from the operating frequency and hence safe from resonance. Merticaru *et al.* [7] addressed the influence of geometrical parameters and technological conditions on the jump phenomenon in the cam-follower contact loss. The case study in this paper focused on a profiled grooved disk cam and oscillating follower. Two dynamic models were developed to study the influence of the cam-follower contact elasticity on the jump phenomenon. The influence of the applied load on the mechanism, the clearance in the cam-follower kinematic pair, the rotational speed of the cam, and the inertia moment were tested using computer simulation.

This paper assesses the fatigue life of a cycloidal displacement cam and a flat-faced follower under the specified load and constraints. The CAD model of the cam-follower is developed in CATIA software and imported to ANSYS software for fatigue analysis. MATLAB programming is developed for determining the appropriate spring constant and pre-load force to always keep the cam and follower in contact. FEA-based fatigue analysis is conducted to estimate the fatigue life of the cam-follower under the specified operating conditions. The analysis method can be applied to study the fatigue life of cams with other profiles, including the modified trapezoidal functions, polynomial functions, etc. Finally, conclusions are drawn.

2. CAD Modeling of the Cam-Follower Mechanism

CAD- and FEA-based computer simulations play a crucial role in the design, evaluation, and modification of cam-follower mechanisms. This study builds a cam-follower CAD model first using the CATIA software for the subsequent FEA-based fatigue life assessment. The cam has a cycloidal displacement profile, and the follower has a flat face as shown in Figure 1. The harmonic acceleration function of the cycloidal displacement cam meets the constraint of zero magnitudes at each end to match the dwell segments that adjoin it. The cycloidal displacement function is obtained by integrating the harmonic acceleration function twice. The undetermined coefficient in the functions can be evaluated by boundary conditions, stroke length, and period of the non-dwell segments. It is assumed that both the cam and follower are made of steel with a density of 7.85×10^{-6} kg/mm^3 in this study. The design parameters are shown in Table 1.

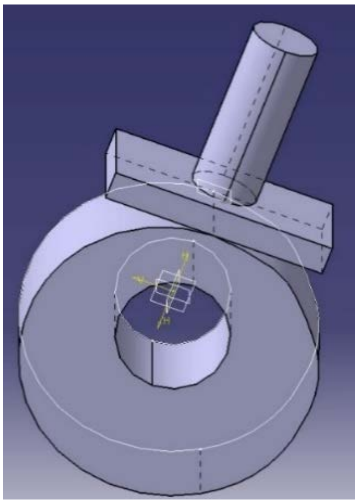

Figure 1. CAD model of the cam-follower mechanism.

Table 1. Design parameters of the cam and follower in this study.

Base circle radius:	20 mm	Flat face:	20 mm × 40 mm
Stroke length:	10 mm	Follower mass:	0.058 kg
Rise segment angle:	150˚	Cam mass:	0.272 kg
Fall segment angle:	190˚	Cam angular velocity:	62.8 rad/s

3. FEA-Based Fatigue Life Assessment of the Cam-Follower Mechanism

The above-developed CAD model is imported to ANSYS for FEA fatigue analysis, as shown in Figure 2. Solid elements are used in discretization. The mechanical properties of the steel used in this study are as follows: density $\rho = 7.85 \times 10^{-6}$ kg/mm^3, yield strength $\sigma_y = 250$ MPa, tensile ultimate strength $\sigma_u = 450$ MPa, Poisson's ratio $\nu = 0.3$, and bulk modulus $K = 1.67 \times 10^5$ MPa.

Mesh convergence is investigated by decreasing the element size gradually and analyzing the impact on the cam deformation. The changes in the maximum cam deformation to the element size are shown in Table 2. Based on the mesh convergence analysis, we choose 1 mm as the default element size in the discretization processing. In the domain being closer to the cam surface, however, finer meshes are used for capturing the contact stress gradients between the cam and follower for more accurate simulation results.

To avoid the follower jump in operation, a compression spring force is applied to the cam joint to keep the cam and follower in contact at all times. The required spring force depends on the cam profile, stroke length, assembly mass, angular velocity, spring constant, and pre-load force. MATLAB programming is developed to determine the cam force based on $F_c = ma + kx + F_{pl}$, where the F_c is the cam force acting on the follower, k is the spring constant, and F_{pl} is the pre-load provided by the spring. By trial and error, we choose the pre-load force of 300 N and the spring constant of 25 kN/mm to maintain positive F_c at any time in the cycle.

Because of the inherent complexity, it is difficult to develop analytical models to assess the contact stress between the cam and follower. Most research on this nonlinear behavior focuses on FEA-based numerical simulation. This study applies the 3-D surface-to-surface contact pairs to the contact zone between the cam and the follower, in which the follower's flat face is taken as the target one. In addition, the cam is constrained to have a rotational degree of freedom about the camshaft and the follower has a translational degree of freedom along the vertical direction only as shown in Figure 3 in the following fatigue analysis.

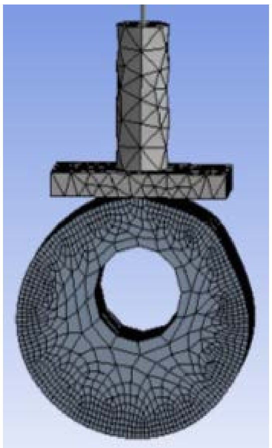

Figure 2. FEA model of the cycloidal displacement cam and flat-faced follower.

Table 2. Mesh convergence for element size ranging from 5 mm to 1.5 mm.

Element Size (mm)	Maximum Cam Deformation (mm)	Changes in Deformation
5	5.0597	-
4	5.0630	0.07%
3	5.0649	0.04%
2	5.0669	0.04%
1.5	5.0675	0.01%

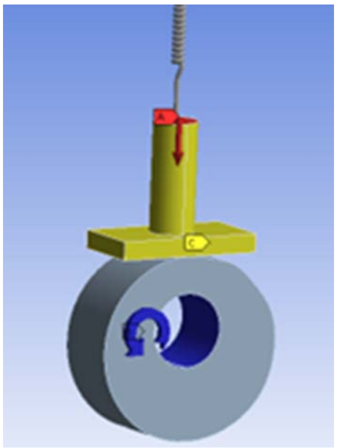

Figure 3. Cam-follower mechanism under specified loads and constraints.

The fatigue life of the cam-follower mechanism is assessed using the modified Goodman criterion based on the fatigue failure stress-life method [8]. The alternative stress and mean stress are expressed in the von Mises stress format. Animated results from the ANSYS post-processing illustrate the changes in the von Mises stress and cam deformation of the cam-follower mechanism for a period of one second, i.e., ten revolutions under the given angular velocity. It is found the cam-follower has a fatigue life of 3.123×10^5 cycles under the specified operating conditions.

4. Conclusion

This study investigates the fatigue life of a cam-follower mechanism. The CAD model of a cycloidal displacement cam and a flat-faced follower is built using CATIA software and imported to ANSYS software for subsequent fatigue life assessment. MATLAB programming is developed for estimating the spring constant and pre-load force to always keep the cam and follower in contact. The appropriate values are determined to be 25 kN/mm and 300 N, respectively. It is found that the cam-follower has a fatigue life of 3.123×10^5 cycles under the specified operating conditions. This study can be applied to investigate the fatigue life of cams with other profiles (modified trapezoidal functions, polynomial functions, for example) in the future.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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