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A Simulation Based Approach to Model Design Influence on the Fatigue life of a Vented Brake disc

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Abstract

The brake disc is considered a safety critical components in vehicles, hence the growing concern on its service life performance. Brake disc performance is measured by several criteria of which prominent amongst these criteria is fatigue life and disc thermal deflection. This study considers the influence of geometric design features of a vented brake disc on its fatigue life at particular sections of the brake disc which are considered critical and its deflection due to thermal inputs. A parametric study is carried out with CAE/FEA using Taguchi design of experiment. The study identified the geometric design features that significantly influence the studied performance measures. Sensitivity plots were also obtained to show the manner these design factors affect the fatigue life at these points as well as the disc thermal deflection. Two design features, the inboard plate thickness and the length of the effective offset are observed to contribute majorly to the fatigue life of the brake disc as well as its thermal deflection. Hence, design effort should be concentrated on these features for optimal fatigue life design at these points of interest in this study.

Keywords: Degradation; Fatigue; Finite element; Service life; Taguchi

1. Introduction

Mechanical damage of structural materials of machine components are generally attributable to factors such as load, temperature, corrosion, time and their interactions, which in connection with component design features, manufacturing process and mechanical properties can intensify the damage [1]. One of such predominant damage mechanisms is fatigue [2]. According to Stephen et al. [3] between seventy and ninety percent of mechanical damage of structures are as a result of fatigue during the course of their operations. One such component prone to fatigue damage is the brake disc. Fatigue in the form of thermal fatigue is a problem of the brake disc as a result of its being subjected to alternating thermal loads (heating and cooling), and constrained in a manner that restricts its free contraction and expansion [4].Studies have indicated that damage of the brake disc as a result of thermal cracking is a low cycle thermal-mechanical fatigue [5], and that critical design load cases for the brake discs are most often related to the thermal load [6] . Thus, for a proper investigation of the life of the brake disc a study of thermal effects on the brake disc has to be done.

Nomenclature

b	Fatigue strength exponent
c	Fatigue ductility exponent
E	Elastic modulus, MPa
σ_y	Ultimate tensile stress, MPa
ε_f'	Fatigue ductility coefficient

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Researchers have studied the thermal effects on brake disc performance and life using methods such as experiments [4] , empirical analysis [5] and with numerical methods [7,8]. In the use of these methods, finite element modelling, a numerical method has found consistent usage in the study of brake discs. In this regard, Belhocine and Bouchetara [8] using a numerical method, finite element analysis modelled the temperature distribution in a disc brake to identify the factors and the entering parameters associated with the time of braking such as the braking mode, geometric design and the brake material. Tirovic [9] also applying finite element analysis identified the disc cooling to aerodynamic efficiency ratio as a useful parameter to assess in developing new brake design or the comparing of different railway brake disc designs. Using both experiments and finite element modelling [10] studied the effect of hole layout on crack initiation in the brake disc. Okamura and Yumoto [11] carried out a series of Computer Aided Engineering/Finite Element Analysis (CAE/FEM) experiments using Taguchi method to demonstrate the effect of basic configurations of brake discs on their thermal behaviour. Their results showed good correlation with experimental data. Duzgun [12] using finite element modelling studied the effect of ventilated disc configurations on thermo-mechanical behaviour of these discs. Based on their study of three different configurations of ventilated disc, they came to the conclusion that the design of the heat dissipation surface of the brake disc has a significant influence on the thermal stress behaviour of these brakes. These researches show the benefit of using finite element modelling for the thermal analysis as well as development of the brake disc. The use of FEM can lead to considerable savings in time and money as it does not involve physical experiments that can be costly and time consuming.

The influence of design features on mechanical components has not received much attention as most studies in component degradation are mostly limited to degradation of material used against the operating or environmental conditions thus leading to the need for increased understanding of design influence on the service life of products [13]. In this research, a study of the influence of geometric design parameters on the thermal fatigue life of a vented brake discs is presented as well as the methodology for carrying out the study. Previous studies have focused on the temperature and thermal stress behaviour of the brake disc but not on the influence of design features on brake disc thermal fatigue life. A design of experiment approach using Computer Assisted Engineering (CAE) and Finite element analysis (FEA) was utilized. Taguchi method of experimental design was used to determine the relative significance of geometric design parameters on the fatigue life of the brake disc at critical sections of the disc, and the disc thermal deflection which also has an influence on brake disc service life, as well as the sensitivity of the thermal fatigue life and deflection of the brake disc to these parameters.

2. Methodology

To achieve the purpose of the work which is a study of the influence of geometric design features on brake disc thermal life, an integrated CAE and a design of experiment approach incorporating finite element analysis was used. The research method involved a simulation of the thermal stresses on the brake discs as result of brake application from which the fatigue life is then determined. The thermal stress and fatigue life of the brake discs are determined through use of finite element analysis a numerical method. The procedure for carrying out the methodology is grouped into several stages. A developed FE model incorporating the brake disc geometry is developed at the initial stage. Next a thermal analysis is performed on the brake disc model to determine the temperature and thermal stresses as a result of brake application. The thermal fatigue life is determined at the third stage using the temperature and thermal stresses obtained in the second stage as inputs. The fourth stage involves a parametric study of the brake discs geometric design parameters using the Taguchi method which is a design of experiment method. Based on the design of experiment matrix obtained the relative influence of the design parameters on the chosen life performance measures of the brake disc is determined as well as parameter sensitivity.

2.1 Taguchi method

Taguchi method which has found wide application is a design of experiment method that is used for minimizing product performance variation, and for getting the performance characteristic as close as possible to the targeted mean. Taguchi method is based on orthogonal array (OA) experimental matrix. The use of OA causes a reduction in the variance for the experimental runs resulting in optimum setting of the product/process parameters. Coupled with the use of OA, Taguchi proposed the analysis of product variation using an appropriately selected measure called Signal-to-Noise ratio (SN ratio) which is derived from the quality loss function [14] and can be used as the objective function for optimisation purposes. An advantage of the SN ratio is that it can reflect the variability in the response, and does not induce unnecessary complications such as control factor interactions. The use of Taguchi analysis of the SNR involves three kinds of quality characteristics; smaller the better, larger the better, and nominal the better.

Larger the better,

$$SN\ Ratio = -10log10\left[\frac{1}{n}\sum_{i=1}^{n}(1/Y_i^2)\right] \quad (1)$$

Smaller the better,

$$SN\ Ratio = -10log10\left[\frac{1}{n}\Sigma_1^n(Y_i^2)\right] \quad (2)$$

Nominal the best,

$$SN\ Ratio = -10log10(S_i^2/Y_i^2) \quad (3)$$

Where n is the number of experiments and Y_i the measured ith quality, which is response indicator.

3. The case study

This case study is concerned with the identification of the geometric design features that significantly influence certain