



Structural optimization of an asymmetric automotive brake disc with cooling channels to avoid squeal

Andreas Wagner*, Gottfried Spelsberg-Korspeter, Peter Hagedorn

fmb, Dynamics and Vibrations Group, Graduate School CE, TU Darmstadt, Dolivostr. 15, 64293 Darmstadt, Germany

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ABSTRACT

Brake squeal is still a major issue in the automotive industry due to comfort complaints of passengers and resulting high warranty costs. Many measures to avoid squeal have been discussed in the engineering community reaching from purely passive measures like the increase of damping, e.g. by the application of shims, to the active or semiactive suppression of squeal. While active measures can be effective but are elaborate and therefore more expensive, passive measures are less complex in most cases. This leads to the necessity to develop passive, economic and robust measures to avoid squeal. Asymmetry of the brake rotor has been proposed to achieve this goal and the resulting split of all double eigenfrequencies of the brake rotor has lately been shown to stabilize the system.

Thus, a structural optimization of an automotive brake disc with cooling channels is presented in this paper with the objective to split all eigenfrequencies of the brake rotor in a certain frequency range by introducing asymmetry to the cooling channels. Constraints of the optimization are balance constraints, to guarantee a balanced operation for all rotor speeds, and minimal and maximal distance constraints of the cooling ribs, due to cooling and material strength requirements. First, a modeling approach of the brake disc with cooling channels is shortly presented which helps to avoid remeshing during the structural optimization. The introduced optimization problem is known to be highly nonlinear, nonconvex and with many local optima to be expected. Therefore, two approaches for the solution of the problem are chosen. The first, a deterministic one, is a Sequential Quadratic Programming (SQP) approach efficiently targeting local optima. In order to increase the possibility to find the global optimum, a set of randomly distributed starting configurations is chosen, leading to satisfying results. The other, a heuristic approach, uses a Genetic Algorithm (GA) directly aiming for the global optimum. The GA also delivers very satisfying results, nevertheless, the best solution has been found with the SQP approach. In order to validate the basic idea that a defined separation of eigenfrequencies helps to avoid squeal, modal analysis and squeal tests have been performed with a simplified disc with radial holes. The conducted experiments strongly support the theoretical findings and demonstrate the superior squeal behavior of the optimized disc.

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1. Introduction

For many decades, design engineers all over the world have been confronted with the objective to find measures against brake squeal. Brake squeal is not only a major issue in the automotive industry where it leads to high warranty costs due to

* Corresponding author. Tel.: + 49 6151 16 2879; fax: + 49 6151 16 4479.

E-mail addresses: wagner@dyn.tu-darmstadt.de (A. Wagner), speko@dyn.tu-darmstadt.de (G. Spelsberg-Korspeter), hagedorn@dyn.tu-darmstadt.de (P. Hagedorn).

passenger's comfort problems, which can easily reach more than 100 million Dollar per year [1]. But it can also lead to serious safety problems in bicycles or motorcycles with lightweight rims [2,3]. The engineering community agrees that the root cause for brake squeal are self-excited vibrations originating from the frictional contact between brake pad and brake disc. An overview about brake squeal in general can e.g. be found in [4], a more general overview over friction induced vibrations in [5]. Currently, in the automotive industry, mainly two analysis approaches are taken to assess the susceptibility of a brake system to squeal: The so-called complex eigenvalue analysis, reducing the analysis of the stability problem of the rotating rotor in frictional contact to an eigenvalue problem, and the transient analysis based on the direct time integration of the underlying equations of motion [6]. Nevertheless, brake squeal and the affinity of brakes to squeal are affected by many different influences, reaching from wear and operating conditions to complicated tribological behavior and temperature dependence of the brake pads, making the simulation of squeal difficult and prone to errors. The influence of the special tribology between brake disc and brake pad is discussed e.g. in [7]. However, there can also be found many minimal models for brake squeal describing the onset of squeal as an instability resulting from nonconservative friction forces with a constant coefficient of friction, leading to circulatory terms in the stiffness matrix [8,9]. In order to be able to predict the amplitude of the limit cycle oscillations during squeal, nonlinear effects have to be taken into account [10,11]. Partially resulting from simulations, partially from experiments, many countermeasures are proposed in the engineering community to avoid squealing. They reach from the introduction of damping into the brake system, by choosing pad or rotor materials or the application of shims, to the active or semiactive suppression of squeal [12,13]. On the one hand, the active squeal countermeasures can be very effective against squeal but are elaborate to tune and expensive. On the other hand, the passive measures are not generally able to avoid squeal completely but are less complex and expensive. Thus, it is highly desirable to find passive, robust and economic countermeasures. Nishiwaki et al. [14] and Fieldhouse et al. [15] proposed the introduction of asymmetries to the brake rotor to achieve this goal. There can also be found patents concerning the subject [16,17]. While these approaches mainly originate from experimental work and partially aim for the splitting of two (or very few) eigenfrequencies in direct vicinity to each other and the squeal frequency, the splitting of all eigenfrequencies of the rotor in a certain frequency range has lately been shown mathematically to stabilize the brake system and avoid squeal [18]. This insight motivates a systematic structural optimization of the brake rotor to split all its double eigenfrequencies [19].

A structural optimization of a realistic automotive brake disc with a variation of the cooling channels to split all double eigenfrequencies in a certain frequency range has not yet been discussed in the literature (to the best of the authors knowledge) and will be the main focus of this paper. The frequency range in which the splitting is necessary will also be estimated in this paper. This optimization problem has been shown to be nonlinear, nonconvex and with many local optima to be expected [20] with nonlinear constraints originating from the requirement to keep the brake disc statically and dynamically balanced. Furthermore, there are minimal and maximal distance constraints to be taken into account due to cooling and material strength requirements.

An overview over the topic of structural optimization can be found in [21,22]. Since most structural optimization problems are in fact nonlinear, the authors refer to [23] for a more general overview of nonlinear optimization. Frequently, structural optimization is divided into sizing, shape and topology optimization. While sizing only allows the variation of some predefined dimensions of a product, shape optimization allows more freedom in the design of the geometry by a more flexible (and changeable) parametrization of the boundaries [24]. Finally, topology optimization allows the maximum amount of freedom in the design space by a possible change even in the topology of a structure [21]. Some topology optimization algorithms are discussed in [25,22]. However, frequently it is desired to allow large changes in the geometry with a detailed description of the boundaries, which cannot directly be achieved with topology optimization. Therefore, level set methods for this kind of structural optimization have been proposed [26,27]. In this paper, an alternative approach to parameterize the geometry will be used, which also allows large variations in the geometry in detail and avoids time-consuming remeshing prone to errors [28]. This method has been introduced in [29]. Often, the underlying nonlinear optimization problems during structural optimization are solved with gradient-based algorithms [22], e.g. with Sequential Quadratic Programming (SQP) methods [30]. These methods can be efficient for problems which do not exhibit too many local optima (since they only converge locally for most nonlinear optimization problems [23]), especially if it is possible to derive design sensitivities analytically or at least semi-analytically [28,31]. However, for noncontinuous problems [32] or problems with many local optima, their performance might be poor. Therefore, also heuristic or metaheuristic approaches are proposed in the context of structural optimization, which have the potential to approach the global optimum. They reach from rather well-known genetic algorithms [33,34] over particle swarm [35] and firefly [36] algorithms to the so-called harmony search algorithm [37], just to name a few. Also they have the advantage that they do not require design sensitivities or gradients, which will be beneficial for the optimization strategy proposed in this paper.

The paper is organized as follows. First, a modeling strategy for the automotive brake disc with cooling channels is proposed, which allows large changes in the geometry of the disc without the necessity to remesh the structure in every iteration step. Then the minimal necessary distance between the eigenfrequencies of the (asymmetric) brake disc is calculated together with the according frequency range. Next, the nonlinear, nonconvex optimization problem to split all eigenfrequencies of the disc is introduced based on the insights gained before with the arising balance and minimal and maximal distance constraints. Two approaches are presented to solve the proposed optimization problem. A deterministic SQP approach with randomly distributed starting points leading to very satisfying results and a heuristic genetic algorithm (GA) also leading to good results. A comparison between the two approaches follows before an experimental validation of the basic idea behind the optimization follows. A short summary then concludes the paper.

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