International Journal of Mechanical Sciences 114 (2016) 207–216

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Numerical and experimental investigation of the torsional stiffness of flexible disc couplings

Bin Zhao, Ying Zhao, Jianmei Feng*, Xueyuan Peng

Xi'an Jiaotong University, No. 28 West Xianning Road, Xi'an 710049, Shaanxi, PR China

ARTICLE INFO

Article history:
Received 8 December 2015
Received in revised form
30 April 2016
Accepted 12 May 2016
Available online 20 May 2016

Keywords:
Finite element
Disc coupling
Torsional stiffness
Bolted flange joint

ABSTRACT

Disc couplings are widely used in compressors, gas turbines, and aerospace applications because of their flexibility and their consequent ability to compensate in almost all directions. The torsional stiffness of disc coupling has a great influence on shaft torsional vibration, and in many applications low-order torsional resonance may occur due to insufficient stiffness in the disc coupling. Investigation of the factors influencing the torsional stiffness of disc coupling will help to improve the design and control of shaft torsional vibration. In this paper, a 3D finite element (FE) model was built to estimate the stiffness of a disc coupling, taking the behavior of friction and contact into consideration. Based on this model, the curve of torque vs. angular displacement was obtained by applying a series of torsional load steps to the coupling. The effects of diaphragm shape, bolt preload, and fluctuation of torque were evaluated. A test rig was established to validate the simulated results. Both the simulated and experimental results demonstrated a strong nonlinear relationship between the torque and angular displacement during both the loading and unloading processes. The results also showed that the bending and inclining of flanges and diaphragms were mainly responsible for the varied stiffness of the disc coupling. In addition, load fluctuation, bolt preload, and shape of diaphragms could lead to variation in the stiffness of disc couplings.

1. Introduction

Couplings are frequently used to connect the coupled shafts of two rotating pieces of machinery. Flexible couplings are increasingly preferred to rigid couplings due to their flexibility and consequent ability to accommodate misalignments in the axial, radial, and angular directions. There are four kinds of industrial flexible coupling: mechanically flexible coupling, elastomeric coupling, metallic membrane coupling, and miscellaneous coupling [1]. As a branch of metallic membrane coupling, flexible disc coupling is characterized by non-lubrication, suitability in a wide range of temperatures, and relative tolerance to chemical attack. Therefore, it is commonly used in turbines, compressors, and aerospace applications.

Torsional vibration exists in all rotating systems. Large vibration amplitudes or torsional resonance will induce excessive alternating stress on shafting, which gives rise to aggravated noise levels, the fracture of the anchor bolts, and fatigue failure of the shaft [2–5]. Flexible coupling has proven to be the most practical method of vibration control, outperforming the other two commonly used methods (stiffening the driveshaft and raising flywheel inertia) [6]. An appropriate torsional flexible coupling shifts the natural frequencies lower and away from the operating speed. While choosing a flexible coupling for a rotating system, either during the design stage or when handling field vibration, torsional stiffness is a crucial parameter. Thus it is of great importance to precisely calculate the torsional stiffness of a flexible coupling.

Many researchers have contributed to the literature on the stiffness and corresponding dynamic behavior of flexible couplings. Ma and Han [7] established non-linear motion equations for a rotating system coupled by flexible coupling, and examined the effect of impact moment on the non-linear stiffness of flexible coupling. Chakrabarti [8] used a modified test rig to study the torsional stiffness of flexible rubber couplings, as well as dynamic stiffness and the linearity ranges of the stiffness curves. Feng et al. [9] calculated the axial stiffness of a trunnion joint and investigated the effects of rotation speed on its axial stiffness. Shentu et al. [10] derived design equations based on a simplified model of laminated membrane coupling to calculate the torsional stiffness and axial stiffness. Further study showed that the joint bearing had no influence on the axial stiffness of laminated membrane coupling but had a significant influence on the radial stiffness. Francis [11] compared three approaches for obtaining

* Corresponding author.
E-mail address: jmfeng@mail.xjtu.edu.cn (J. Feng).

http://dx.doi.org/10.1016/j.ijmecsci.2016.05.012
0020-7403/

torsional stiffness values in metal disk couplings: an analytical method, a numerical method using a full 3D FEA model, and an experimental method used in industry. In the FEA model, the coupling was treated as a rigid connection. The FEA results were found to be within 10% of the experimental results; however, the results of the theoretical method of calculation were within 38% of the FEA results. Notomi [12] evaluated the effect of bending moment on four kinds of diaphragm couplings using finite element analysis, and proposed two ways to develop torsional stiffness. Saavedra [13] deduced a new coupling stiffness matrix and used it to calculate the mechanical vibration of a two-rotor system connected by a flexible coupling as considering angular and parallel shaft misalignments with residual unbalance. The results and analysis indicate that the vibration generated by shaft misalignment is caused by the variation in coupling stiffness on rotation, and that the forcing frequencies generated are harmonics of the shaft's speed and directly depend on the frequency of the variation in coupling stiffness. Investigation of bending moment on couplings showed a great influence on torsional stiffness and dynamic response.

In a common disc coupling, the flexible element component is alternately attached by bolts to an input and output flange, with all the bolts being on the same pitch circle diameter. In this structure, the component is clamped by bolts along the circumference, in the same manner as the distribution of the flange joint. The simplest method of analyzing a bolted flange joint is to treat it as a rigid connection, disregarding any possible influence of the joint on the response. This method can achieve good agreement between the predicted and measured resonance frequency, while the damping effects due to the nonlinear friction behavior of the flange are neglected [14]. A better approach is to take into consideration the stiffness of the bolt and energy dissipation due to the friction between the two contact surfaces [15–18]. A full three-dimensional modeling of the contact interface with nonlinear contact elements may be the most precise approach. It requires input parameters for the contact surfaces, such as friction coefficient and contact stiffness. Schwingshackl et al. [19] took advantage of the third approach to consider good nonlinear modeling practice and obtain the required nonlinear data. Kim et al. [20] introduced four kinds of finite element models to investigate modeling techniques for bolted joints. All of the proposed methods take the pretension effect and contact behavior between the flanges into account. Wu et al. [21] used an FEA method to investigate the nonlinear deformation behavior of a preloaded bolted flange joint under tensile, torsional, and bending loads to determine the corresponding stiffness values for each loading. Yuan et al. [22] used a three-dimensional finite-element contact method to investigate the stress distribution of a curvic coupling, while taking non-linear behaviors such as friction and contact into consideration. Jiang et al. [23] established a three-dimensional finite element model for a bolted joint with curvic coupling to study the details of the self-loosening process of the bolt under dynamic torque loads. However, the actual structure of a disc coupling is much more complex than that of a bolted flange joint, and its behavior may well be similarly complex.

This literature review reveals that the effect of bolt preloading on a disc coupling under torque loads has never been reported. Little attention has been paid to the effects of relative motion between the parts of disc couplings on torsional stiffness during the process of loading, and to how the coupling would react after the loosening of the bolt. In this paper, a quasi-static modeling approach using FEA is applied to obtain the flexible disc coupling's torsional stiffness during a loading and unloading process, taking into account the behavior of friction and contact on all of the contact interfaces. The effect of bending moment was not included to highlight the effect of torque. Furthermore, the impact of load fluctuation, bolt preload, diaphragm type, and flange stiffness on torsional stiffness is examined. An experimental test rig was set up to validate the simulated results.

2. Numerical analysis

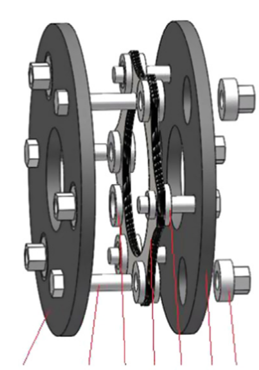
2.1. Geometry model

A common flexible disc coupling, as shown in Fig. 1, consists of an input flange, laminated component, bolts, gaskets, ringers, lock nuts, and output flange. The two parallel flanges separate six bolts into two groups, which connect the laminated component on the input and output sides. The laminated component includes 11 metallic diaphragms with a thickness of 0.4 mm. The 11 diaphragms were simply piled together and were able to slip. The detailed dimensions of the disc coupling are shown in Table 1.

2.2. Finite element modeling

To obtain the torsional stiffness characteristics of the disc coupling, a finite element model was generated using commercial software. The model representing the disc coupling was meshed using eight-node hexahedral brick elements, which have the capacity to represent large deformations and the non-linearity of both the geometry and the material. To simulate the bend of the diaphragms, there should be enough layers through thickness; using two layers for every diaphragm yielded results that were both satisfactory and time-saving. Contact between the connection components was modeled using the surface-to-surface interaction command with a small sliding option. The coefficients of static friction and kinetic friction were measured according to method described by Jiang [23]. Average coefficients of static friction and kinetic friction was set at 0.34 and 0.3, respectively, for the contacting interfaces. To obtain better convergence, the contact pairs in this model were meshed at the same size. The entire FE model of the disc coupling is shown in Fig. 2(a). There are 420,594 elements in the model. The FE models of the diaphragms, ringers, and bolts are shown in Fig. 2(b).

To determine the relation between the torsional stiffness and transmitted torque of the coupling over a complete loading and unloading process, the entire simulation was processed in the following four load steps. The first load step was used to set a boundary condition on the coupling by restricting all the degrees of freedom on the nodes on the inner surface of the output flange. The second load step was to apply a preload to the bolts in the form of a pretightening force in the bolts' axial direction. The initial load was set to 0.1% of the total force and the minimum increment of the substeps was set to 1e-5 to improve the contact



1 Input flange, 2 Bolt, 3 Gasket, 4 Laminated component, 5 Ringer, 6 Output flange, 7 Lock nut

Fig. 1. Structure of flexible disc coupling.