Engineering Analysis with Boundary Elements 56 (2015) 20–29

Contents lists available at ScienceDirect

Engineering Analysis with Boundary Elements

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

Analyzing the load distribution of four-row tapered roller bearing with Boundary Element Method

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ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form
26 January 2015
Accepted 30 January 2015
Available online 24 February 2015

Keywords:
Boundary Element Method
Bearing boundary element
Hertz contact theory
Four-row tapered roller bearing
Shaft block direct measure method

ABSTRACT

A Boundary Element Method (BEM) is used to study the roller bearing contact problem due to its high non-linearity. The plate units are used to simulate the rollers, the bearing boundary elements are used to realize the discontinuous nature of the traction on the contact area, and the Hertz contact theory is used to revise contact widths between rollers and the inner and outer races. According to assembly and fit characteristics of rolling mill tapered roller bearings, in which both clearance fits are adopted to the inner race with the mill roll and the outer race with the shaft block, the four-objects elastic frictional contact program of bearing BEM is compiled, with which a rolling mill four-row tapered roller bearing is simulated. The shaft block direct measure method is used to measure the load distribution of the four-row tapered roller bearing. The experimental data and the result of simulation are compared, and the load distribution laws of simulation identify with the test result, which proves the validity and effectiveness of using elastic frictional contact BEM to analyze the load distribution of bearing.

1. Introduction

As a key part of mill, multi-row roller bears the big radial load, axial load and thermal load at work, that make multi-row roller bearing generate partial load easily and the bearing life drop dramatically. The accidents of abnormal loss and large area fatigue spalling happen frequently, which restrict the production seriously [1]. The load and its distribution of multi-row roller bearings are the main factors affecting the running behavior, and the peak contact stress affects the fatigue life of the bearing system directly. Therefore, study on the number of bearing rollers, the magnitude of load and the maximum load of rollers etc. has a great significance to confirm bearing system service life and reliability [2].

Calculating the accurate load distribution of bearing has become an issue that many researchers concern doubly [3–5]. Since the Boundary Element Method (BEM) has advantages of dimension reduction and response parameters on the contact boundary can be obtained directly, many scholars used BEM to study contact problems [6–8], especially the load distribution of mill roller bearing [9,10]. Shu et al. [11] proposed that roller bearing inner race with roll was assumed tight fit as one object, bearing outer race with shaft block was assumed tight fit as one object, and the calculation of the three-dimensional load distribution is under assumed contact widths of rollers with the inner and outer races.

Four-row tapered roller bearing can bear radial and axial load at the same time; therefore it is commonly used in heavy and medium plate mill. In production, in order to change the mill roll frequently and rapidly, both loose fits were adopted to the inner race with the roll and the outer race with the shaft block when the four-row tapered roller bearing was used [12]. Therefore, according to the characteristics of the roller bearing, based on the four-objects elastic frictional contact BEM, the plate units are used to simulate the rollers, bearing boundary elements are used to realize the discontinuous nature of the traction on the contact area, and the Hertz contact theory is used to revise contact widths between rollers and the inner and outer races. The accurate bearing load distribution can be worked out with the iterative calculation.

2. Bearing BEM

2.1. Plate units

The roller bearing system belongs to multi-object contact problem. In order to simplify the calculation model of roller bearing, the plate units which are fixed on the inner race are used to simulate the rollers. The width of plate unite is the contact width between rollers and the outer race, the length of plate unite

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http://dx.doi.org/10.1016/j.enganabound.2015.01.013
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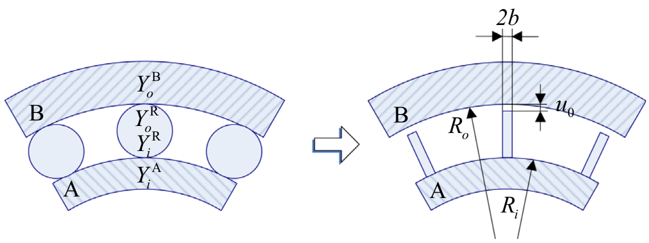

Fig. 1. Contact situation among roller, inner race and outer race.

is the length of roller on axial direction [10]. Fig. 1 shows the contact situation among rollers, inner race and outer race, in which object A is the inner race and object B is the outer race.

In roller bearings, only the radial displacement of rollers influences the contact status. When the rollers are considered as plate unites, which has radial displacement only, substituting the radial displacement of plate units to the totality matrix equation that has no influence on the calculation accuracy.

$$\Delta u_{\xi_3}^{Y_i^A,m} = \frac{2}{\pi l}\Delta t_{\xi_3}^{Y_i^A,m}\left[\frac{1-\mu_i^2}{E_i}\left(\ln\frac{2R_i}{b_i}+0.407\right)+\frac{1-\mu^2}{E}\left(\ln\frac{2R}{b_i}+0.407\right)\right] \tag{1}$$

$$\Delta u_{\xi_3}^{Y_o^B,m} = \frac{2}{\pi l}\Delta t_{\xi_3}^{Y_o^B,m}\left[\frac{1-\mu^2}{E}\left(\ln\frac{2R}{b_o}+0.407\right)+\frac{1-\mu_o^2}{E_o}\left(\ln\frac{2R_o}{b_o}+0.407\right)\right] \tag{2}$$

$$b_i = 1.522\sqrt{\frac{\Delta t_{\xi_3}^{Y_0^A,m}RR_i}{E_i l(R+R_i)}},\ b_o = 1.522\sqrt{\frac{\Delta t_{\xi_3}^{Y_0^B,m}RR_o}{E_o l(R_o-R)}} \tag{3}$$

where R_i represents the outer diameter of the inner race, R_o represents the inner diameter of the outer race, R represents the radius of the rollers (for tapered roller bearings, take the average radius), l represents the length of rollers, E, E_i and E_o represent the elastic modulus of rollers, inner race and outer race respectively, μ, μ_i and μ_o represent Poisson's ratio of rollers, inner race and outer race respectively, $\Delta u_{\xi_3}^{Y_i^R,m}$ and $\Delta u_{\xi_3}^{Y_o^R,m}$ represent the displacement of nodes Y_o^R and Y_i^R in the direction of ξ_3 under the local coordinate system respectively, $\Delta t_{\xi_3}^{Y_i^A,m}$ and $\Delta t_{\xi_3}^{Y_0^B,m}$ represent the displacement of nodes Y_o^R and Y_i^R in the direction of ξ_3 under the local coordinate system respectively.

Considering the elastic deformation of rollers, the clearance of the $(m+1)$-th incremental load is expressed as follows:

$$\delta_{m+1} = \delta_0 - \left(\Delta u_{\xi_3}^{Y_i^A,m} - \Delta u_{\xi_3}^{Y_o^B,m} + \Delta u_{\xi_3}^{Y_R^i,m} + \Delta u_{\xi_3}^{Y_R^o,m}\right) \tag{4}$$

2.2. Bearing boundary element

In the total-contact models of mill roll, bearing and shaft block, in order to separate the bearing contact elements from the ordinary contact elements when taking the traction characteristics of roller bearing into consideration, bearing boundary elements are used to simulate the bearing contact elements. Taking inner race for example, Fig. 2 shows the discrete model of inner race and the position relationship of rollers. Assuming the number of rollers as n, the inner race can be divided into $2n$ bearing boundary elements along the circumferential direction.

One bearing boundary element is divided into two sub-elements, there is continuous traction on sub-element Γ_i^1 and the traction is zero on sub-elementΓ_i^2. Assuming normal traction on the sub-elements of Γ_i^1 presents parabolic distribution along the width direction and linear distribution along the length direction

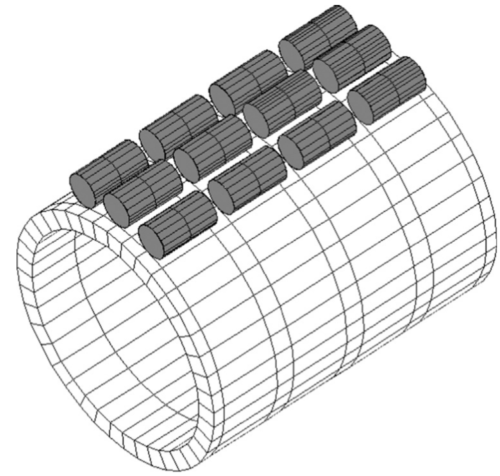

Fig. 2. The sketch map of discrete inner race.

[9]. As shown in Fig. 3, there are two kinds of bearing boundary elements, BBE1 and BBE2. In BBE1, nodes 3 and 4 are contact nodes, and in BBE2, nodes 1 and 2 are contact nodes.

Due to the effect of friction and the incremental load, the incremental traction on sub-element Γ_i^1 is expressed as follows:

$$\begin{cases} \Delta t_{\xi_3}^{m,i,I} = \sum\limits_{\beta=3}^{4} F_I^{\beta}(\xi_1,\xi_2)\Delta t_{\xi_3}^{m,i,\beta} \\ \Delta t_{\xi_3}^{m,i,II} = \sum\limits_{\beta=1}^{2} F_{II}^{\beta}(\xi_1,\xi_2)\Delta t_{\xi_3}^{m,i,\beta} \end{cases} \tag{5}$$

$$\begin{cases} F_I^{\beta}(\xi_1,\xi_2) = (1+(-1)^{\beta}\xi_1)\,(\xi_2-\xi_2^0)^2/2(1-\xi_2^0), \beta=3,4 \\ F_{II}^{\beta}(\xi_1,\xi_2) = (1+(-1)^{\beta+1}\xi_1)(\xi_2-\xi_2^0)^2/2(1+\xi_2^0), \beta=1,2 \end{cases} \tag{6}$$

where I and II represent the type of bearing boundary elements BBE1 and BBE2 respectively, ξ_1, ξ_2 and ξ_3 represent the direction under local coordinate system, $\Delta t_{\xi_3}^{m,i,I}$ and $\Delta t_{\xi_3}^{m,i,II}$ represent the increment normal traction of sub-element Γ_i^1 of BBE1 and BBE2 respectively when the m-th step increment is loaded, $\Delta t_{\xi_3}^{m,i\beta}$ represents the increment normal traction of the β-th node of element i when the m-th step increment is loaded, N_β^I and N_β^{II} represent the interpolation functions of BBE1 and BBE2 respectively, and ξ_2^0 represents the coordinate values of inside edge of sub-element Γ_i^1, in the direction of ξ_2 $(1-\left|\xi_2^0\right|$ is half width of contact area).

The aspect ratio of sub-elements Γ_i^1 is so large that larger errors will be caused in the integral calculation. Therefore, it needs to be further divided into multiple bearing boundary micro-elements, and the bearing boundary micro-element aspect ratio should be limited to under 3. The aspect ratio of the bearing boundary micro-element with a singular point is equal to one [9]. The schematic plan of bearing boundary micro-elements is shown in Fig. 4.

Each bearing boundary micro-element's area is $\xi_a \le \xi_1 \le \xi_b$ and $\eta_a \le \xi_2 \le \eta_b$. Gaussian integration should be conducted under area of $-1 \le \xi \le 1$ and $-1 \le \eta \le 1$. Therefore, the coordinates of all bearing boundary micro-elements need to be transformed as follows:

$$\begin{cases} \xi_1 = \dfrac{\xi_a-\xi_b}{2}\xi + \dfrac{\xi_a+\xi_b}{2} \\ \xi_2 = \dfrac{\eta_b-\eta_a}{2}\eta + \dfrac{\eta_b+\eta_a}{2} \end{cases} \tag{7}$$