Ball’s motion, sliding friction, and internal load distribution in a high-speed ball bearing subjected to a combined radial, thrust, and moment load, applied to the inner ring’s center of mass: Numerical procedure

Mário César Ricci
Space Mechanics and Control Division, National Institute for Space Research, Av. dos Astronautas, 1758, 12227-010, São José dos Campos, SP, Brazil
E-mail: mariocesarricci@uol.com.br

Abstract. In a companion paper of this was introduced a set of non-linear algebraic equations for ball’s motion, sliding friction and internal loading distribution computation in a high-speed, single-row, angular-contact ball bearing, subjected to a known combined radial, thrust and moment load, which must be applied to the inner ring’s center of mass. It was shown there that it is required the iterative solution of $9Z + 3$ simultaneous non-linear equations – where $Z$ is the number of balls – to yield exact solution for contact angles, ball attitude angles, rolling radii, normal contact deformations and axial, radial, and angular deflections of the inner ring with respect the outer ring. The Newton-Rhapson method is to be used to solve the problem. This paper deals with the numerical procedure description. The numerical results derived from the described procedure shall be published later.

1. Introduction

When an external load is applied to one of the rings of a rolling bearing it is transmitted through rolling elements to the other ring. Because the internal load distribution on the rolling elements is an important operating characteristic of a bearing a great number of authors have addressing the problem. A literature review on the subject can be found in [1] and [2], in which a mathematical model for necessary radial displacement between rings, and a mathematical model for external radial load, so that the $q$-th rolling element passes to participate in the load transfer were presented.

In [3] a model was developed, which enables a very simple determination of the number of active rolling elements participating in an external load transfer, depending on the bearing type and internal radial clearance.

In [4] the theoretical analysis of a single-row radial bearing with radial clearance under constant external radial load was presented. The analysis was focused on finding the rolling element deflection that allows determining the number of active rolling elements that participate in the load transfer. Taking into account the bearing internal geometry, a mathematical model to calculate the rolling elements deflections during the bearing rotation has been derived.

In [5], [6] and [7] capacitive probes were inserted into the fixed ring of the bearing such that forms with the raceway a capacitor with variable gap that depends on the transmitted load by the rolling element. A numerical model of this capacitor’s capacitance as a function of transmitted load by the rolling element has been established. An experimental prototype has been established in order to
precisely measure the probe’s capacitance. Finally, this technique has been generalized with a capacitive probe in front of each rolling element. Thus, knowing the load transmitted by each of the rolling elements, the external load on the bearing of the rotating machine can be easily reconstructed.

The evaluation of change in contact angle due to applied load is vital in order to study the load carrying capacity of large diameter bearings. Analytical and numerical procedures have been developed to calculate various design factors such as contact angle, contact stress and deformation. In [8] the change in contact angle of balls was determined by using FEA. The change in contact angle was compared with analytical, FEA and the Newton-Raphson method. The results show a good agreement with the values calculated using Hertz’s relations for deformation. The FEA method was used to get the nodal solution of contact angle, contact stress and deflection for various loading conditions.

In [9] the dynamic modeling of a centrally supported symmetrical disk-shaft bearing system has been analyzed using Timoshenko beam elements. Intermittent ball bearing contact forces and Muszynska’s force [10] at seal-disk interface were considered in the model to simulate a real-time system. Results show that there was a marked effect of each type of nonlinear excitation on the overall system response.

In [11] a wheel bearing life prediction method, which considers the bearing dynamics characteristics, was proposed. The results were compared with existing formulas and static analyses results from structural dynamics commercial software.

In [12] a unidirectional compression spring was used to model the contact between a rolling element and the raceway of a heavy-duty slewing bearing accounting for the supporting structure flexibility and the plastic deformation of the bearing. The spring constant was determined by the load against elastic-plastic deformation relationship of a single rolling element, which was obtained by finite element contact method. The difference between the traditional Hertz contact results and the FEM results is very obvious for the slewing bearings with plastic deformation, such as contact deflection of the rolling elements and the raceway, load distribution on the rolling elements, stress in the raceway and contact pressure between the rolling elements and the raceway. Therefore, the method based on the Hertz contact mechanics theory is not applicable for the performance analysis of the heavy-duty slewing bearing.

The focus of this paper is to describe the numerical procedure for ball’s motion, sliding friction and internal load distribution computation in a high-speed, single-row, angular contact ball bearing, subjected to a known combined radial, thrust and moment load, which must be applied to the inner ring’s center of mass. In a companion paper of this [13] a set of non-linear algebraic equations was introduced in order to accomplish this task. It was shown there that it is required the iterative solution of 9Z + 3 simultaneous non-linear equations – where Z is the number of balls – to yield exact solution for contact angles, ball attitude angles, rolling radii, normal contact deformations and axial, radial, and angular deflections of the inner ring with respect the outer ring. The Newton-Rhapson method is to be used to solve the problem.

2. Symbols

\( \begin{array}{ll}
\text{a} & \text{Semimajor axis of the } \text{projected contact, m; elements of square matrix} \\\n\text{b} & \text{Semiminor axis of the } \text{projected contact, m} \\\n\text{c} & \text{Short for } \cos \\\n\text{d} & \text{Bearing pitch diameter, m} \\\n\text{D} & \text{Ball’s diameter, m} \\\n\text{f} & \text{r/D} \\\n\text{F} & \text{External, friction or centrifugal forces, N} \\\n\text{J} & \text{Ball’s mass moment of } \text{inertia, kgm}^2 \\\n\text{K} & \text{Load-deflection factor, N/m}^{0.5} \\\n\text{m} & \text{Ball’s mass, kg} \\\n\text{M} & \text{External, gyroscopic or frictional moments, Nm} \\\n\text{r} & \text{Raceway groove curvature radius, m} \\\n\text{r’} & \text{Rolling radius, m} \\\n\text{s,s} & \text{Distance between loci of inner and outer raceway groove curvature centers, m} \\\n\text{X} & \text{Radius to locus of raceway groove curvature centers, m} \\\n\text{V} & \text{Radial projection of distance between ball center and outer raceway groove curvature center, m; slip velocity of the race on the ball, m/sec} \\
\end{array} \)
3. Numerical procedure

Equations (16)-(18), (22)-(24), (27)-(29), and (54)-(56) of [13] may be written as

\[ \epsilon_g(h_0) = 0, \quad g, h = 1, ..., 9Z + 3, \]  
(1)

in which \( \delta_i = V_i, \ldots, \delta_Z = V_Z, \delta_{Z+1} = W_1, \ldots, \delta_{2Z+1} = \delta_{1}, \ldots, \delta_{3Z} = \delta_{Z}, \delta_{3Z+1} = \delta_{1}, \ldots, \delta_{4Z} = \delta_{Z}, \delta_{4Z+1} = r_{1}, \ldots, \delta_{5Z} = r_{Z}, \delta_{5Z+1} = r_{1}, \ldots, \delta_{6Z} = \omega_x, \delta_{6Z+1} = \omega_x, \ldots, \delta_{7Z} = \omega_y, \delta_{7Z+1} = \omega_y, \ldots, \delta_{8Z} = \omega_z, \delta_{8Z+1} = \omega_z, \delta_{9Z+2} = \delta_{1}, \delta_{9Z+3} = \delta. \)

The first 9Z equations from (1) must be solved simultaneously for \( \delta_1, \ldots, \delta_{9Z} \) once values for \( \delta_{9Z+1}, \ldots, \delta_{9Z+3} \) are assumed. If \( \delta_0^0 \), \( h = 1, ..., 9Z \), is a 9Z-dimensional vector with the initial estimates of the variables \( \delta_1, \ldots, \delta_{9Z} \), improved values are given by

\[ \delta_0' = \delta_0^0 - \left[ a_{gh} \right]^{-1} \epsilon_g, \]  
(2)

in which \( \epsilon_g \), \( g = 1, ..., 9Z \), is the 9Z-dimensional vector with the first 9Z errors functions from (1).

The elements of the square 9Zx9Z-matrix \( \left[ a_{gh} \right] \) are

\[ a_{jh} = -2(s_{jZ} - \delta_j)\frac{\partial \delta_j}{\partial h} - 2(s_{jZ} - \delta_{Z+j})\frac{\partial \delta_{Z+j}}{\partial h} - 2(f_i - 0.5)D + \delta_{3Z+j}\frac{\partial \delta_{3Z+j}}{\partial h}, \]  
(3)

\[ a_{(j+Z)h} = 2\delta_j\frac{\partial \delta_j}{\partial h} + 2\delta_{Z+j}\frac{\partial \delta_{Z+j}}{\partial h} - 2(f_o - 0.5)D + \delta_{2Z+j}\frac{\partial \delta_{2Z+j}}{\partial h}, \]  
(4)

\[ a_{(j+2Z)h} = 2\delta_{2Z+j}\frac{\partial \delta_{2Z+j}}{\partial h} + 2\delta_{2Z+j}\frac{\partial \delta_{2Z+j}}{\partial h} + 2\delta_{8Z+j}\frac{\partial \delta_{8Z+j}}{\partial h}, \]  
(5)

\[ a_{(j+3Z)h} = \frac{s_{jZ} - \delta_j}{s_{jZ} - \delta_{Z+j}}\frac{\partial \delta_j}{\partial h} + \frac{s_{jZ} - \delta_j}{s_{jZ} - \delta_{Z+j}}\frac{\partial \delta_{Z+j}}{\partial h} + \frac{s_{jZ} - \delta_j}{s_{jZ} - \delta_{Z+j}}\frac{\partial \delta_{3Z+j}}{\partial h}, \]  
(6)

\[ a_{(j+5Z)h} = \frac{\partial F_{y0j}}{\partial h} + \frac{\partial F_{yij}}{\partial h}, \]  
(7)
The forces \( F_{xij} \), \( F_{yij} \) and \( F_{xoj} \) to be used in (6) and (7) are given by (32), (38) and (39) of the companion paper of this [13] and their differentiation with respect to \( \delta_h \), \( h = 1, \ldots, 9 \), yields

\[
\frac{\partial F_{xij}}{\partial \delta_h} = 3 \mu K_{ij} \delta_{xj} \frac{b_{ij}}{2 \pi a_{ij} b_{ij}} \int_{-a_{ij}}^{a_{ij}} 1 - \frac{x_{ij}^2}{a_{ij}^2} - \frac{y_{ij}^2}{b_{ij}^2} \cos y_{ij} \frac{\partial y_{ij}}{\partial \delta_h} \, dx_{ij} + \frac{3}{2} F_{xij} \frac{\partial \delta_{xj}}{\partial \delta_h},
\]

\[
\frac{\partial F_{xoj}}{\partial \delta_h} = 3 \mu K_{oij} \delta_{xj} \frac{b_{oj}}{2 \pi a_{oj} b_{oj}} \int_{-a_{oj}}^{a_{oj}} 1 - \frac{x_{oj}^2}{a_{oj}^2} - \frac{y_{oj}^2}{b_{oj}^2} \sin y_{oj} \frac{\partial y_{oj}}{\partial \delta_h} \, dx_{oj} + \frac{3}{2} F_{xoj} \frac{\partial \delta_{xj}}{\partial \delta_h},
\]

The moments \( M_{xij}, M_{yij}, M_{xoj} \), and \( M_{yoj} \) to be used in (9) and (10) are given by (48), (49), (52), (53), (37) of [13] and their differentiation with respect to \( \delta_h \), \( h = 1, \ldots, 9 \), yields

\[
\frac{\partial M_{xij}}{\partial \delta_h} = -3 \mu K_{ij} b_{ij} \frac{b_{ij}}{2 \pi a_{ij} b_{ij}} \int_{-a_{ij}}^{a_{ij}} \frac{x_{ij}^2}{a_{ij}^2} + \frac{y_{ij}^2}{b_{ij}^2} \sin y_{ij} \frac{\partial y_{ij}}{\partial \delta_h} \, dx_{ij} + \frac{3}{2} M_{xij} \frac{\partial \delta_{xj}}{\partial \delta_h},
\]

\[
\frac{\partial M_{yij}}{\partial \delta_h} = -3 \mu K_{ij} a_{ij} \frac{a_{ij}}{2 \pi a_{ij} b_{ij}} \int_{-a_{ij}}^{a_{ij}} \frac{x_{ij}^2 + y_{ij}^2}{a_{ij}^2} \sin y_{ij} \frac{\partial y_{ij}}{\partial \delta_h} \, dx_{ij} + \frac{3}{2} M_{yij} \frac{\partial \delta_{xj}}{\partial \delta_h},
\]

\[
\frac{\partial M_{xoj}}{\partial \delta_h} = -3 \mu K_{oij} b_{oj} \frac{b_{oj}}{2 \pi a_{oj} b_{oj}} \int_{-a_{oj}}^{a_{oj}} \frac{x_{oj}^2 + y_{oj}^2}{a_{oj}^2} \sin y_{oj} \frac{\partial y_{oj}}{\partial \delta_h} \, dx_{oj} + \frac{3}{2} M_{xoj} \frac{\partial \delta_{xj}}{\partial \delta_h},
\]

\[
\frac{\partial M_{yoj}}{\partial \delta_h} = -3 \mu K_{oij} b_{oj} \frac{b_{oj}}{2 \pi a_{oj} b_{oj}} \int_{-a_{oj}}^{a_{oj}} \frac{x_{oj}^2 + y_{oj}^2}{a_{oj}^2} \sin y_{oj} \frac{\partial y_{oj}}{\partial \delta_h} \, dx_{oj} + \frac{3}{2} M_{yoj} \frac{\partial \delta_{xj}}{\partial \delta_h}.
\]
The moments $M_{ij}$, $M_{yoj}$ and $M_{y'j}$ to be used in (11) are given by (50), (51) and (36) of the companion paper of this [13] and their differentiation with respect to $\delta_h$, $h = 1, \ldots, 9$ yields

\[
\frac{\partial M_{ij}}{\partial \delta_h} = \frac{2 \omega_j \epsilon_{ij}}{2 \pi \nu_{ij} \delta_h} \left( \frac{x_{ij}}{\omega_j} \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j} \right) \left( \frac{x_{ij}}{\omega_j} + \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j} \right) - \left( \frac{x_{ij}}{\omega_j} \right)^2 \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j}.
\]

(20)

As in (38)-(41) and (48)-(53) of [13], also in (13)-(20), (22)-(23) $\gamma_{ij}$, $\gamma_{oj}$ are given by (42) of [13]. The derivatives of $\gamma_{ij}$, $\gamma_{oj}$ with respect $\delta_h$, $h = 1, \ldots, 9$ to be used in (13)-(20), (22)-(23) are given by

\[
\frac{\partial \gamma_{ij}}{\partial \delta_h} = -\omega_j \left( \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j} \right) \left( \frac{x_{ij}}{\omega_j} \right)^2 \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j}.
\]

(24)

As in (38)-(41) and (48)-(53) of [13], also in (13)-(20), (22)-(23) $\nu_{ij}$, $\gamma_{ij}$ are given by (42) of [13]. The derivatives of $\gamma_{ij}$, $\gamma_{oj}$ with respect $\delta_h$, $h = 1, \ldots, 9$ to be used in (13)-(20), (22)-(23) are given by

\[
\frac{\partial \gamma_{ij}}{\partial \delta_h} = \left( \frac{x_{ij}}{\omega_j} \right)^2 \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j}.
\]

(25)

in which $V_{ij}/\omega_{ij}$, $V_{ij}/\omega_{ij}$, $V_{ij}/\omega_{ij}$, $V_{ij}/\omega_{ij}$ and $V_{ij}/\omega_{ij}$ with respect $\delta_h$, $h = 1, \ldots, 9$, to be used in (25) are given by

\[
\frac{2 \omega_j \epsilon_{ij}}{2 \pi \nu_{ij} \delta_h} \left( \frac{x_{ij}}{\omega_j} \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j} \right) \left( \frac{x_{ij}}{\omega_j} + \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j} \right) - \left( \frac{x_{ij}}{\omega_j} \right)^2 \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j}.
\]

(26)

\[
\frac{\partial \gamma_{ij}}{\partial \delta_h} = -\omega_j \left( \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j} \right) \left( \frac{x_{ij}}{\omega_j} \right)^2 \frac{\partial V_{ij}}{\partial \omega_j} \frac{\partial \nu_{ij}}{\partial \nu_{ij}} \frac{\partial \omega_j}{\partial \omega_j}.
\]

(27)
For the outer race to be stationary, \( \omega_{m_j} \) and \( \omega_{R_j} \) are given by (33)-(34) of [13]. The derivatives of (33) and (34) of [13] with respect to \( \delta_h, h = 1, \ldots, 9Z \), to be used in (12), (21) and (24) are given by

\[
\frac{\delta V_{oj}}{\delta h} = \delta \begin{bmatrix}
\left( \frac{1}{\omega_m} - \frac{1}{\omega_R} \right) - \frac{1}{\omega_m} - \frac{1}{\omega_R} \left( \delta_{2x} - \delta_{2y} \right) - \delta_{2z} \left( \delta_{2x} - \delta_{2y} \right) - \delta_{2z} \left( \delta_{2x} - \delta_{2y} \right) - \delta_{2z} \left( \delta_{2x} - \delta_{2y} \right) - \delta_{2z} \left( \delta_{2x} - \delta_{2y} \right) - \delta_{2z} \left( \delta_{2x} - \delta_{2y} \right) - \delta_{2z} \left( \delta_{2x} - \delta_{2y} \right)
\end{bmatrix}
\]

Likewise, for the inner race to be stationary,
and \( \partial (\partial_2 \delta \omega) / \partial \delta \) is given by (31) with the opposite sign.

The last three equations from (1) must be solved simultaneously for \( \delta Z_{9+1}, \ldots, \delta Z_{9+3} \) after obtaining updated values for: \( \beta_{ij}, \beta_{oj}, K_{ij}, K_{oj}, s_{xj}, s_{zj}, F_{xij}, F_{yij}, F_{xoj}, F_{yoj}, M_{sij}, M_{s oj}, M_{Rij}, M_{R oj}, \partial_2 \delta Z_{9+j}, k = 0, \ldots, 8; j = 1, \ldots, Z \). If \( \delta h_k, h = 9Z+1, \ldots, 9Z+3, \) is a 3-dimensional vector with the initial estimates of the variables \( \delta Z_{9+1}, \ldots, \delta Z_{9+3} \), in that order, improved values are given by (2), in which \( \{ \varepsilon \}, g = 9Z+1, \ldots, 9Z+3, \) is the 3-dimensional vector with the errors functions, in that order, from (1). The elements of the 3x3-matrix \( \left[a_{gh}\right] \) are

\[
\begin{align*}
\alpha_{9Z+1h} &= \frac{\delta F_a}{\delta h_i} \sum_{j=1}^{Z} \left[ \frac{[f_{i}-0.5)D+\delta Z_{j+1}]}{\delta h} \left( K_{ij} \frac{\partial \delta Z_{j}}{\partial h} + s_{xj} \frac{\partial \delta Z_{j}}{\partial h} \right) \left( \frac{\partial \delta Z_{j}}{\partial h} \right) \right] \\
\alpha_{9Z+2h} &= \frac{\delta F_a}{\delta h_i} \sum_{j=1}^{Z} \left[ \frac{[f_{i}-0.5)D+\delta Z_{j+1}]}{\delta h} \left( K_{ij} \frac{\partial \delta Z_{j}}{\partial h} + s_{xj} \frac{\partial \delta Z_{j}}{\partial h} \right) \left( \frac{\partial \delta Z_{j}}{\partial h} \right) \right] \\
\alpha_{9Z+3h} &= \frac{\delta F_a}{\delta h_i} \sum_{j=1}^{Z} \left[ \frac{[f_{i}-0.5)D+\delta Z_{j+1}]}{\delta h} \left( K_{ij} \frac{\partial \delta Z_{j}}{\partial h} + s_{xj} \frac{\partial \delta Z_{j}}{\partial h} \right) \left( \frac{\partial \delta Z_{j}}{\partial h} \right) \right]
\end{align*}
\]

Differentiating (16)-(18), (22)-(24) and (27)-(29) of [13] with respect \( \delta h, h = 9Z+1, \ldots, 9Z+3, \) simultaneous linear equations in \( \partial \delta_2 \delta Z_{9+j} / \partial \delta h, k = 0, \ldots, 8; j = 1, \ldots, Z, \) results, which are

\[
\begin{align*}
\left( s_{xj} - \delta \right) \frac{\partial \delta Z_{j}}{\partial h} &+ \left( s_{xj} - \delta \right) \frac{\partial \delta Z_{j}}{\partial h} + \left( f_{i}-0.5)D + \delta Z_{j+1} \right) \frac{\partial \delta Z_{j+1}}{\partial h} = \\
\left( s_{xj} - \delta \right) \frac{\partial \delta Z_{j}}{\partial h} &+ \left( s_{xj} - \delta \right) \frac{\partial \delta Z_{j}}{\partial h} + \left( f_{i}-0.5)D + \delta Z_{j+1} \right) \frac{\partial \delta Z_{j+1}}{\partial h}
\end{align*}
\]
The derivatives of $F_{z'j}$, $F_{xij}$, $F_{xoj}$, $F_{yij}$, $F_{yoj}$, $M_{sij}$, $M_{soj}$, $M_{Rij}$, $M_{Roj}$, $M_{z'j}$, $M_{yij}$, $M_{yoj}$ and $M_{y'j}$ with respect $\delta_h$, $h = 9Z+1, \ldots, 9Z+3$, to be used in (33)-(44) are given by (12)-(24). In (13)-(20), (22)-(23) $\gamma_{ij}$, $\gamma_{oj}$ are given by (42) of [13]. The derivatives of $\gamma_{ij}$, $\gamma_{oj}$ with respect $\delta_h$, $h = 9Z+1, \ldots, 9Z+3$, to be used in (13)-(20), (22)-(23) are given by (25), with $V_{xij}/\omega_{sij}$, $V_{yij}/\omega_{sij}$, $V_{xoj}/\omega_{soj}$ and $V_{yoj}/\omega_{soj}$ given by (43)-(46) of [13]. The derivatives of $V_{xij}/\omega_{sij}$, $V_{yij}/\omega_{sij}$, $V_{xoj}/\omega_{soj}$ and $V_{yoj}/\omega_{soj}$ with respect $\delta_h$, $h = 9Z+1, \ldots, 9Z+3$, to be used in (25) are given by (26)-(29).

For outer race to be stationary $\omega_{mj}/\omega$ and $\omega_{Rj}/\omega$ are given by (33)-(34) of [13] and for inner race to be stationary are given by (35)-(34) of [13], the last with opposite sign. The derivatives of (33)-(34) of [13] with respect $\delta_h$, $h = 9Z+1, \ldots, 9Z+3$, to be used in (12), (21) and (24) are given by (30)-(31) and for (32) and (31), the last with opposite sign, are given by (32)-(31), the last with opposite sign.

The (36)-(44) linear system’s solutions $\partial \delta_{kZ+j}/\partial \delta_h$, $k = 0, \ldots, 8; j = 1, \ldots, Z$ – are to be used in (33)-(35) for the new estimates of $\delta_{9Z+1}, \delta_{9Z+2}$ and $\delta_{9Z+3}$.

4. References

[1] Tomović R 2012 Mechanism and Mach. Theory 47 74-88
[2] Tomović R 2012 Int. J. Mech. Sci. 60 23-33
[3] Tomović R 2013 Adv. Mat. Res. 633 103-16
[4] Tudose C, Rusu F and Tudose L 2013 Appl. Math. Mech. 56 469–74
[5] Rasolofonandraibe L, Pottier B, Marconnet P and Chiementin X 2012 IEEE Sens. J. 12 2186–91
[6] Rasolofonandraibe L, Pottier B, Marconnet P and Perrin E 2013 IEEE Sens. J. 13 3067–72
[7] Murer S, Bogard F, Rasolofonandraibe L, Pottier B and Marconnet P 2015 Mech. Syst. Signal Process. 54-5 306–13
[8] Starvin M S, Christopher A S and Manisekar K 2011 CiIT Int. J. Automation and Autonomous Syst. 3 389–94
[9] Rajasekhar M, Srinivas J, Divekar A 2013 Proc 1st Int. and 16th Nat. Conf. on Machines and Mechanisms (iNaCoMM2013) 941-46
[10] Muszynska A 1986 J. sound vib.110 443-62
[11] Seong S, Kim W, Bae D and Lee S 2014 Korean Soc. Mech. Eng. Fall Annual Meet. 776-79
[12] Zhenguo S, Huimin D, Fanhai M and Hua W 2011 Trans. CSAE 27 52-6
[13] Ricci M C 2015 Journal of Physics: Conference Series 641 012017