ISSN 2229-5518

Dynamic Modeling and Sensitivity Analysis of Cam Swing- Roller Follower System

Nurudeen A. Raji[1], Rasheed O. Durojaye[2] and Abiodun A. Yussouff[3]
[1]Department of Mechanical Engineering, Lagos State University, Ojo, Nigeria
[2]Department of Structures and Aerodynamics, National Space Research and Development Agency, Lagos, Nigeria
[3]Department of Computer Engineering, Grace Polytechnic, Omu, Nigeria

Abstract: The paper deals with the modeling and sensitivity analysis of a swing roller follower system designed for the operation of the beat-up mechanism of a narrow loom weaving machine. The translation and torsion models were developed for the system using the Newton's second law of motion. The models were simulated in a MATLAB application. The performance and dynamics of the cam system are analyzed using the SIMULINK technique. The data obtained from the simulation is used for a partial sensitivity analysis of the system's model. The sensitivity calculations were performed so that the deviation in the desired outputs of the system due to variation in the systems inertia parameters is minimized. The parameters chosen with respect to the sensitivity analysis are the mass inertia, spring stiffness and the damping coefficients. The spring stiffness and damping coefficients were kept constant while the mass inertia of the cam plate, follower link and beater link were varied to obtain a robust sensitivity of the system. The analysis is used to characterize the mass of necessary materials required for the manufacture of the cam system's plate, follower and beater links for optimum system operation.

Keywords: cam, follower, beater, sensitivity, modeling, response, displacement, vibration, inertia parameter

1. Introduction

Cam-follower system is an intermittent motion mechanical device used to for the transmission of motion in a machine by direct contact of the follower and cam feature. The cam feature is the driver while the follower is the driven member. The cam-follower systems are usually designed for specified motion characteristic required for a desired machine operation usually of high speed. The mechanism is widely used in printing press machinery, shoe machinery, textile machinery and internal combustion engines (Huang, et al. 2013, Patel 2015). An important task in the design of cam-follower system is the determination of the cam profile needed to induce the required motion on the follower and cam profile error could bring a damaging dynamic performance of high-speed follower cam system.

The motion characteristic of the follower often depends on the profile of the cam (Wu, Chang and Liu 2007). The design of the cam profile which determine the kinematics of the follower had been a subject of discourse over the years. The reverse turn principle of the traditional graphic method are sometimes used for the design of cam profile having complicated motion in rise and return travel using Pro/E software (Sun and Luo 2010). (Raji and Adegbuyi 2003) extends the envelope theory for cam design to the swinging roller follower cam in which the profile of the plate cam was developed. The equation for the cutter point coordinates of the profile was derived and the cam profile was obtained for the specified motion of a narrow strip weaving loom. In (Xiao and Zu 2009) and (Sateesh 2014), non-uniform rational B-spline approach was developed for improving the cam follower performance through the redesign of its cam profile. The approach used the B-spline curve to represent the follower motion and a CAD/CAM system was used to develop for the follower, the distance, velocity, acceleration, jerk, pressure angle and cam profile for the B-spline. The deviation in the cam profile contour was a challenge to the follower kinematic output (Chang & Wu, 2009a; Nguyen & Kim, 2007) and the use of computer modeling for the design of cam profile in order to annihilate such challenges had been attempted by (Alaci, et al., 2011; Pourghodrat & Nelson, 2011).

The efficiency of the cam manufacture had also been found to determine the kinematics of the follower. Optimum tolerance design and synthesis ensures good quality product at low cost (Zhang & Wang, 1993; Singh, et al., 2004). A computerized approach based on the simulated higher-pair contact analysis was developed to minimize the influence of manufacture tolerance of the cam on the follower kinematics for disc cam mechanisms with a flat-faced follower and roller follower (Chang & Wu, 2009b) The tolerance analysis results show that, the follower motion was influenced considerably due to the combine effects of the design parameters. (Hsieh 2011) proposed method which employed homogenous coordinate transformation and conjugate surface theory to develop a kinematic model for cam profile design.

The cam profiles are often modified by advance design methods based on dynamic synthesis and optimization such as the polydyne methods of algebraic polynomial and the envelope theory. (Kirana and Srivastavab 2013) used the algebraic polynomial method to specify the follower motion as a back substitution for the determination of the cam profile. A 3-4-5 polynomial cam profile with extended control providing a zero acceleration at the end points of stroke was obtained. (Wang, et al. 2012) developed the parameterized design system of disc cams with translating roller follower using the AutoCAD tool. Earlier attempt by (Yu and Lee 1998) analyzed the size of the cam disc in a cam mechanism with translating roller follower using non-linear programming techniques and family of parametric polynomials to describe the motion curve. The attempt extensively considered the kinematic feature of the mechanism.

The cam is usually driven by actuator which could be a camshaft or some other mechanism such as the offset slider crank mechanism. The torque fluctuation induces speed fluctuation in the cam which causes distorted follower motions (Demeulenaere and Schutter 2002). The actuators are often desired to operate at constant speed. However for high speed cam follower mechanism, the input speed often fluctuate due to inertia torque required for the camshaft to operate. Input speed balancing method had been used to reduce driving speed fluctuations in high speed machines as discussed in (Demeulenaere, Spaepen and Schutter 2005). The relationship between the follower response and the actuator speed fluctuation had been investigated (Lahr & Hong, 2007; Kuang & Hsu, 2007). The interaction between the follower dynamic response and the actuator driving speed of a roller gear cam system was investigated in (Kuang and Hsu 2007) where the Lagrange equation was used to describe the dynamic intermittent motion equation for the cam system and the effect of torque compensation on the speed fluctuation of the system was iterated to obtain a smooth follower response for the roller gear cam system. (Lahr and Hong 2007) developed a cord and pulley system to double the number of followers in contact with the cam of an infinitely variable transmission cam-follower system in order to reduce the contact stress between the followers and the cam surface towards maintaining a constant input speed of the actuator. (Tounsi, et al. 2011) modeled camshaft eccentricity and cam profile errors to show that the presence of eccentricity on camshaft showed a slight influence on the dynamic behavior whereas the cam profile error showed a substantial increase in the vibration levels.

The effect of the cam profile error on the dynamic behavior of a cam follower system was investigated in (Dickrell-III, Dooner and Sawyer 2003) and (Trabelsi, Chaâri and Haddar 2007) using lumped parameter dynamic model. The cam profile error resulting from the cam manufacturing, cam wear, and cam flexibility was modeled to show that the flexibility of the system affect the follower response of the system. The error introduced causes fluctuations of the follower acceleration. In (Jing and Yan-An 2009) a novel concept of active balancer for reducing the input torque fluctuations of mechanisms was developed. A differential gear train was used for the active active balancer which was driven and controlled by a servomotor. The design was able to minimize the input speed fluctuation of the mechanism. Also cam-based passive element could be added to reduce the peak actuator torque requirement for effective follower response (Realmuto, Klute and Devasia 2015). (Hu, Zhou and Ma 2015) proposed a flexible dynamics model of a high-speed cam mechanism with an oscillating roller follower based on Hertz line contact theory and coefficient of restitution for curbing the possibility of the speed fluctuation of the cam system,

Another major challenges of the cam-follower mechanism is the residual vibration associated with its operation. The undesired dynamic of the follower due to residual vibration is usually due to the elasticity of the mechanism components which often compromise the accuracy of its operation (Gatti and Mundo 2010).

Improving the cam-follower performance and optimization of the system was a major concern to designers. Early optimal design of the cam mechanism with translating flat faced follower using genetic algorithm was discussed in (Tsiafis, et al. 2013). Optimality was considered for cam size, the input torque and the cam-follower contact stress as a multi-objective optimization functions. The constraint was obtained for the weight and the optimization was carried out by using the genetic algorithm approach. In some other study (Chablat and Angeles 2005) the optimization of the pressure angle in a cam-follower transmission was the objective while the influence of the variation in follower radius, rollers and number of lobes in the cam design were considered as the design parameters. The efficiency of the dynamic characteristic of the cam system therefore depends upon the level of control of the input variables for optimal design of the cam system. (Kaplan 2014) also modeled the dynamic behavior of high speed cam follower system and the model was used to optimize cam shape to reduce the residual vibrations in the follower part of the system using the Lagrange multipliers method which focused on minimize the deviation from the cam profile over one period under continuity and smoothness constraints. An emerging method of multidisciplinary design optimization had been used to optimize the distribution cam mechanism for diesel engines (Lei and Jianrun 2013). The new method based on kinematic analysis was used to obtain the parameters for the vibration, contact stress, maximum acceleration and mechanical performance of the system. (Flores 2013) discussed a computational approach for design optimization of disc cam mechanism with eccentric translating roller followers. The cam base circle radius was optimized with geometrical constrained related to the maximum pressure angle and minimum radius of curvature. A numerical method for computation of the base circle radius of the cam had been attempted in (E.-C. Lovasz, et al. 2012) (E. Lovasz, et al. 2013) for oscillating flat-face follower. The numerical method uses the condition of continuous convex for the cam profile to avoid singularities towards achieving positive curvature radius.

It is evident from the above discussion that the geometrical optimization of the cam system had received considerable attentions over the years. In the design of cam-plate it is often desired that the minimum size of the cam base circle is achieved in order to save space, reduce weight, and decrease the inertia effect which might arise from the weight of the cam-plate (Raji 2000). The resulting minimum base circle reduces the pressure angle of the cam such that jamming during operation of the mechanism is avoided. The pressure angle is thus desired to be at its minimum in order to achieve the optimum cam size for the design. There is need to critically substantiate reducing the possible vibration effect of cam system during operation. The present study adopt the concept of sensitivity analysis for the motion of a narrow loom beat-up swing-roller follower system subject to the system's variation in the cams inertia parameters. A procedure to treat unit inconsistency in parameter estimation for understanding the influence of inertial parameters on the dynamics behavior and performance of systems was proposed by (Ebrahimi and Kövecses 2010). The sensitivity analysis could play an important role in making important design decisions for the design of a complex system of the narrow loom beat-up mechanism.

The response of the follower to the variation of the input could be measured by sensitivity analysis of the system in an attempt to obtain optimal performance of the cam follower system. Design sensitivity analysis had been considered as an essential tool for design optimization and trade-off studies (Müller, et al. 1999) (Thai and Beran 2010). Performance sensitivity of a system is a measure of the system performance variation due to the deviation or changes in the design variables of the system. It measures the changes in the performance of the system due to unpredictable variation in selected design parameters for the system. The objective therefore is to minimize the sensitivity value of the system in order to ensure quality performance characters of such system. Sensitivity analysis was used to determine the resulting uncertainty for the output of the system resulting from the variation that may occur in the input. The sensitivity analysis is able to determine how sensitive the output of a system could respond to the change in the input variables. (Hajžman and Polach 2012) develop a model suitable for the solution of the torsional vibration of a gearbox using the sensitivity analysis for tuning the gearbox Eigen-frequencies out of the excitation frequencies of the system.

Most sensitivity analysis is often carried out to observe the influence of the design variables such as the input variables on the variation in response of the system. It has been established that the robustness of such system increases as the sensitivity decreases. (Andrisano, et al. 2011) used the performance sensitivity distribution (PSD) theory to perform the sensitivity characterization of injection molding processes for investigating the variation space of the involving design variables using the regression analysis technique. High computational cost in modeling engineering system could also be avoided through sensitivity analysis in the selection of appropriate design parameters for optimum operation of such system as evident in (Castillo, et al. 2006); (Stephens, Gorissen and Dhaene 2009); (Deihimi 2009). The application of sensitivity calculation for multibody system was discussed by (Wolf, Haase and Claußs 2008) which proved that sensitivity calculation has the potential to pre-evaluate prior parameters of a model. The efficient computation of sensitivity analysis was implicitly discussed by (Serban and Petzold 2002).
The use of sensitivity analysis for the selection of material inertia parameters for the system at the design stage have not been explicitly explored. The rigid body inertia of the components of mechanical systems are essential in predicting the dynamic behavior of the systems (Farhat, Díaz

and Mata 2007); (Kloepper, et al. 2010); (Gholami, et al., 2011); (Kinsheel, et al. 2012). Parameter estimation study for inertia properties have a significant impact on handling and stability of mechanical system (Kolansky and Sandu 2013). (Gholami, Kövecses and Font-Llagunes 2011) investigated the sensitivity and parametric analyses of impact intensity in crutch walking selecting the mass, second moment of inertia, and the location of the center of mass as the parameters of the crutch. (Xiang, Arora and Abdel-Malek 2008) derived sensitivity equations for predicting the motion of a mechanical system for optimal operation using inverse recursive Lagrangian formulation. The proposed formulation was used to demonstrate the optimal time trajectory of the mechanical system. (Neto, Ambrosio and Leal 2008) presents a general formulation for the computation of a first-order analytical sensitivities using automatic differentiation of flexible multibody systems. A direct method for sensitivity calculation was obtained by differentiating the equations that defines the response of the flexible multibody systems with respect to the design variables.

2. Dynamic Modeling

The concept model selected for analysis is the swing roller follower cam mechanism designed for a narrow loom beat-up mechanism of a weaving machine (Raji, et al. 2011). The cam system consists of a radial cam plate driven by a camshaft. A roller swing follower is assembled on the cam plate designed for motion required of a beater slay-bar with reed of a narrow loom. Continuous contact of the follower with the plate cam is ensured by a return spring attached to the follower and a reference frame as shown in Figure 1.

The narrow loom beat-up mechanism is modeled as shown in Figure 2. The inertia effect of the camshaft is assumed negligible. The follower, beater, and the cam disc are considered as rigid bodies for the analysis. The contact between the cam disc and follower roller is modeled by a spring of Hertzian stiffness k_h and the bearing connecting the roller to the follower is modeled by a spring k_f. The expression for the dynamic behavior of the system are obtained as follows;

The dynamic equations generally described in matrix format as expressed in equation (10) could be obtained by the Newton's second law of motion.

$$[\boldsymbol{M}]\{\ddot{\boldsymbol{q}}\} + [\boldsymbol{B}]\{\dot{\boldsymbol{q}}\} + [\boldsymbol{K}]\{\boldsymbol{q}\} = \{\boldsymbol{F}\} \quad 1$$

Where **M**, **B** and **K** are the mass, damping and stiffness matrix respectively. **q** is the degree of freedom vector expressed as;

$$\boldsymbol{q} = \left[\boldsymbol{y_c}, \boldsymbol{y_f}, \boldsymbol{y_b}, \boldsymbol{\theta_c}, \boldsymbol{\theta_f}, \boldsymbol{\theta_b}\right]^{\boldsymbol{T}} \quad 2$$

ISSN 2229-5518

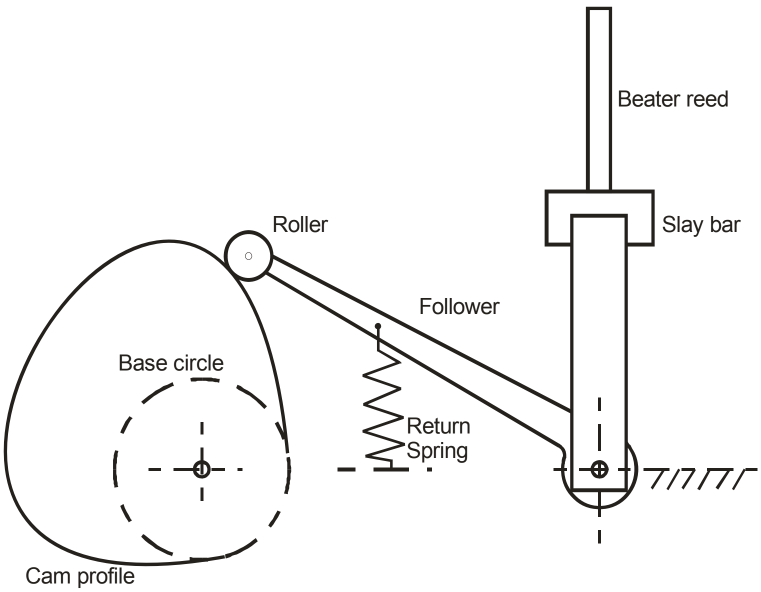


Figure 1. Schematic diagram of the Mechanism.

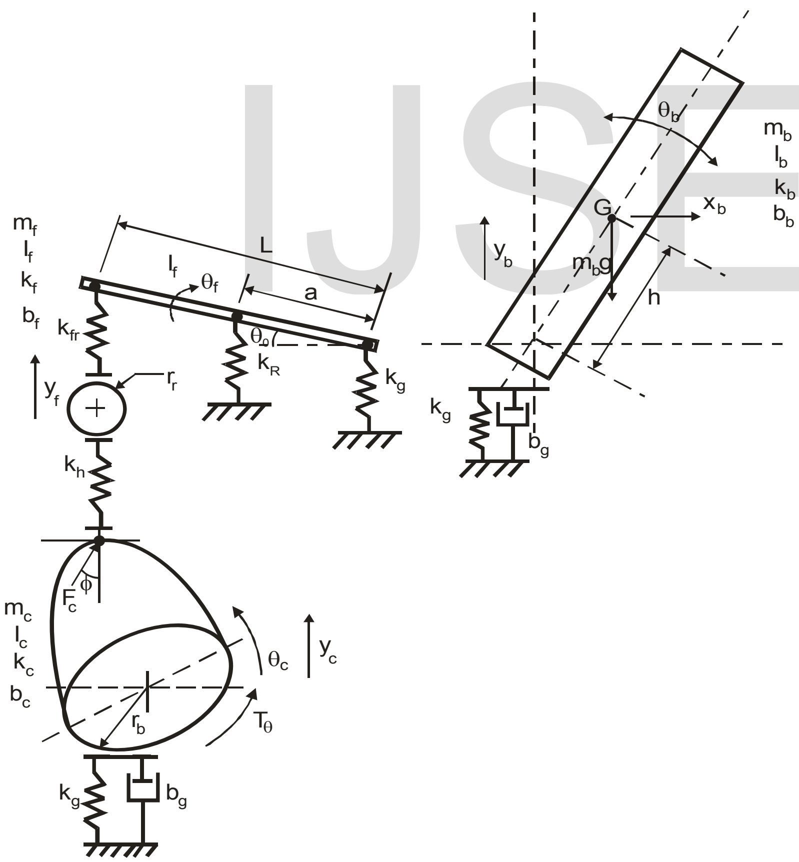


Figure 2. Model representation of the Narrow Loom beat-up Mechanism (Raji, Erameh and Ozor, et al. 2010)

The parameters $\boldsymbol{\theta_c}, \boldsymbol{\theta_f}, \boldsymbol{\theta_b}$ are the system's cam plate, follower link and beater link responses respectively and $\boldsymbol{y_c}, \boldsymbol{y_f}, \boldsymbol{y_b}$ represent the residual vibration of the system's cam plate, follower link and beater link respectively.

The expression for the dynamic response of the system are obtained from the dynamics equations expressed in equations (3-4).

$$I_c\ddot{\theta}_c - b_c\dot{\theta}_c + (k_c + k_{gf})\theta_c - k_{fc}\theta_f + F_c Cos\emptyset \frac{(\dot{y}_f - \dot{y}_c)}{\dot{\theta}_c} = T_\theta \qquad 3$$

$$I_f\ddot{\theta}_f + b_f(\dot{\theta}_f - \dot{\theta}_o) - (k_{fr}L^2 + k_a a^2 + k_f)\theta_f = 0 \qquad 4$$

$$I_b\ddot{\theta}_b + b_b\dot{\theta}_b + k_b(\theta_b - \theta_f) = m_b g h Cos(\theta_b) \qquad 5$$

The expression for the system vibration could be obtained as expressed in equations (6-9)

$$m_c\ddot{y}_c + b_g\dot{y}_c + k_g y_c - k_f(y_f - y_c) = 0 \qquad 6$$

$$m_r\ddot{y}_f + (k_h - k_f)(y_f - y_c) = F_c Cos(\phi) \qquad 7$$

$$m_f\ddot{y}_f + (k_{fr}L - k_R a + k_g)y_f = 0 \qquad 8$$

$$m_b\ddot{y}_b + b_g\dot{y}_b + k_g(y_b - y_c) = 0 \qquad 9$$

F_c is the contact force between the cam and roller and could be expressed as in equation (10) as obtained in (Raji, Erameh and Ajayi, et al. 2011)

$$F_c = \frac{I_f\ddot{\theta}_f}{r_r Cos(\phi)} \qquad 10$$

ϕ is the pressure angle obtained as (Raji, Erameh and Ajayi, et al. 2011);

$$\phi = tan^{-1}\left[\cot(\theta_f - \theta_{fo}) - \frac{L\left(1 - \frac{d\theta_f}{d\theta_c}\right)}{C\sin(\theta_f + \theta_{fo})}\right] \qquad 11$$

Where L is the length of the roller arm,
C is the distance between the cam center and the follower pivot point
θ_f is the follower angular displacement
θ_{fo} is the angular follower displacement at start of motion
θ_c is the cam plate angular displacement

The system performances required for the sensitivity data is obtained from the simulation of the system performance using SIMULINK of the MATLAB software 2007 edition.

3. Dynamic and Sensitivity Analysis

The system sensitivity is a measure of the performance variation of the system due to variation in the system's design variables. The system performance could be affected by the inertia parameters such as the mass, the damper and the stiffness matrices. The sensitivity of the responses to these inertia parameters are of interest. The sensitivity analysis involve simulation analysis in which key parameters are systematically changed to investigate the influence of such changes on the performance outcome of the system. The objective is to determine the values of the inertia parameters that will reduce the residual vibration candidate parameters $\boldsymbol{y_c}, \boldsymbol{y_f}, \boldsymbol{y_b}$ and also minimize the variation in the performance outputs $\boldsymbol{\theta_c}, \boldsymbol{\theta_f}, \boldsymbol{\theta_b}$ due to variation in the inertia parameters.

The inertia parameters are the mass, the damping coefficient and the spring stiffness. The stiffness and damping parameters were assumed constant to allow for partial sensitivity analysis approach which is adopted here. The values of the stiffness and damping parameters are as given in Table 1. In this approach, the value of one variable is changed while holding the values of other variables constant, and the influence of such change is observed on the change in response of the system. The main idea is to pre-evaluate the sensitivity of the performance of the cam mechanism due to variations of single parameter of the system inertias. This will give an insight to the selection of the material required for the fabrication of the cam plate, follower link and beater link for optimum performance.

Table 1. Fixed parameters for system simulation

k_g (kN/mm)	k_f (kN/mm)	k_h (kN/mm$^{3/2}$)	a (mm)	L (mm)	h (mm)	g (m/s^2)	b_g (kN-s/mm)
20	0.7	2	500	200	75	9.81	20

The variation in the performance of the system could be expressed as in equation (12) as adopted from (Andrisano, et al. 2011).

$$\Delta = \left[\frac{dy}{d\boldsymbol{p}}\right][d\boldsymbol{p}]^T \qquad 12.$$

Where **y** represents the residual vibration of the cam plate, follower link and the beater link, and **p** are the inertia parameters representing the mass, stiffness and damping coefficient. The system residual vibration responses of the cam plate, follower link and beater link is shown in Figures 3. The displacement of the cam features are periodic. The beater link is observed to have higher amplitude of 0.8 mm. This could be as a result of the impact action of the beater on the weft during the looms weaving operation. The cam plate and the follower link which are in direct contact with each other in the system arrangement tends to have similar vibration responses with the cam plate and follower having amplitude of 0.45 mm and 0.35 mm respectively. The series arrangement of the cam and follower link could be responsible for the higher cam plate amplitude compared with the follower link. The system's vibration is observed to be underdamped as evident in the low rate at which the amplitude decreases for the cam plate, follower link and the beater link. This suggest that the system need be controlled and therefore require a control system designed for the purpose.

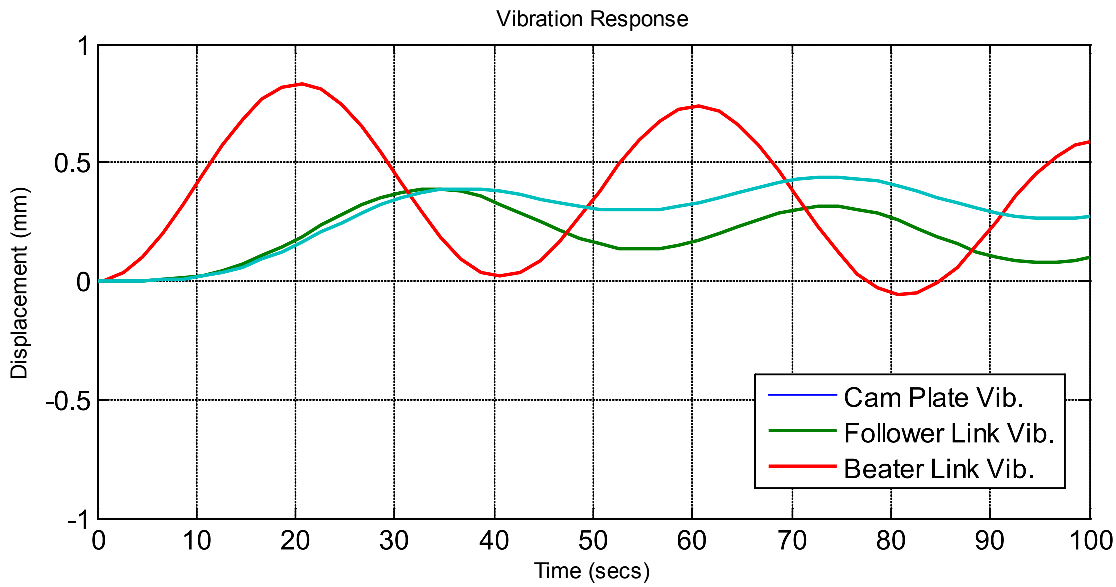
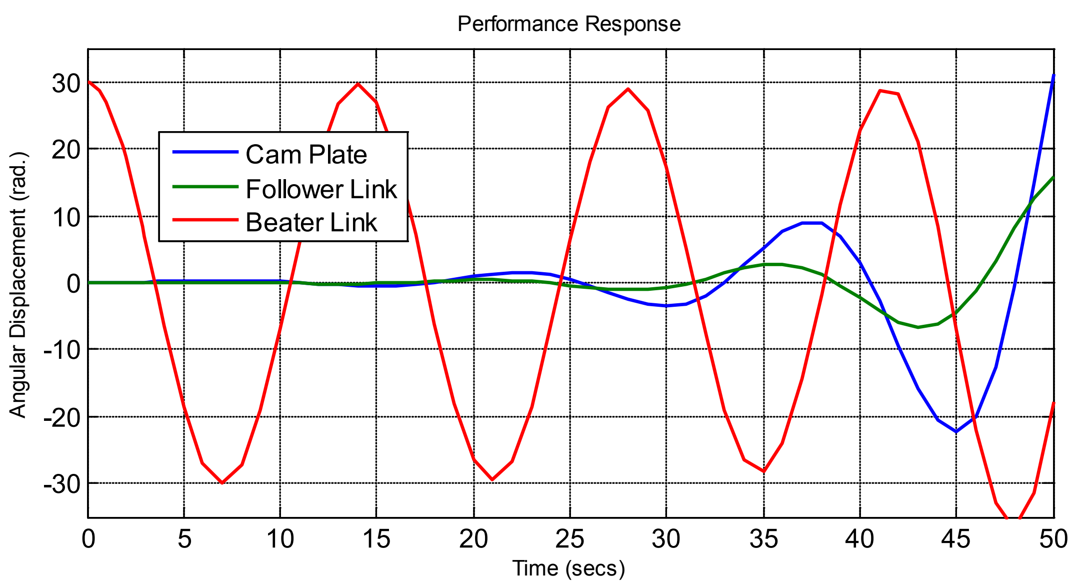


Figure 3. Time fluctuation of displacement of the cam plate, follower link and beater link

Figures 4-5 shows the simulation response of the angular displacement, velocity and acceleration of the cam follower system respectively. Figure 4 shows that the final output of the system from the beater link is periodic with amplitude of 30 rad/sec. and frequency of 0.075Hz. The behavior of the cam plate and follower link shows that both components are in resonance because the response increases indefinitely. The amplitude of the response can be seen to increase linearly with time suggesting serious vibration influence on the cam follower system which implied that the system needed to be controlled.



ISSN 2229-5518

Figure 4. Nonlinear dynamic behavior of the system angular displacement

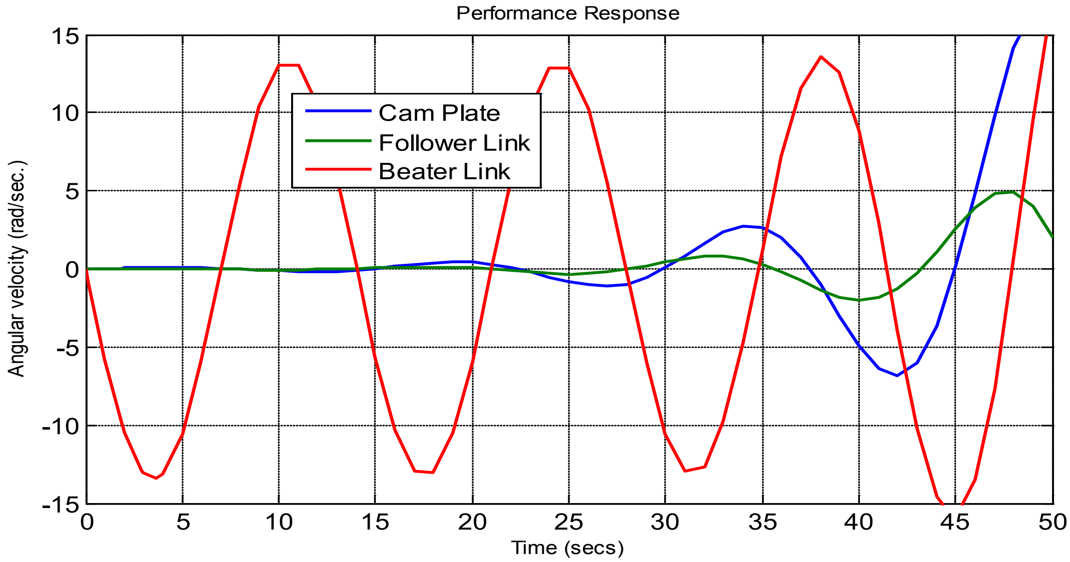


Figure 5. Nonlinear dynamic behavior of the system angular velocity

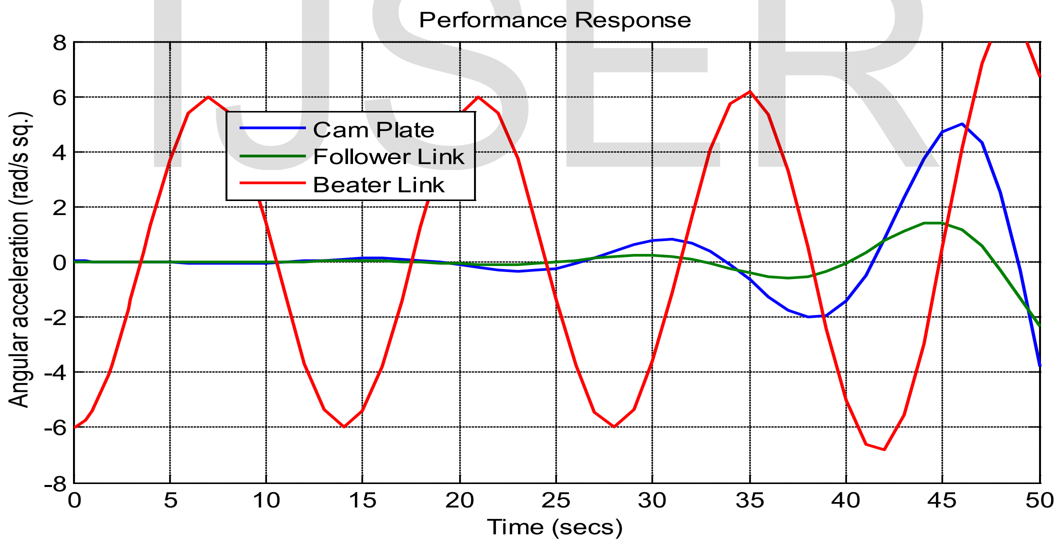


Figure 6. Nonlinear dynamic behavior of the system angular acceleration

Figures 7-9 shows the variation in the sensitivity parameters with respect to the variations in the inertia parameters. Forty-two sets of simulations were performed, using variations in the masses of the cam plate, follower link and beater link respectively. For each case the amplitude of the vibration was recorded and compared with the previous. Figure 7 shows that the variation in the mass of the cam plate has negligible influence on the performance of the beater link. The sensitivity of the system reduces at mass range of 0.02 kg for the follower and cam plate. The influence of the mass of cam plate on the sensitivity of the follower could be as a result of the continuous contact of the follower and the cam plate which is ensured by the return spring. Figures 7 and 8 shows that variation in the mass of the cam plate and follower link has insignificant influence on the sensitivity of the system. The system sensitivity became constant between mass variations of 0.02 – 0.1 kg.

Figure 9 shows the sensitivity of the nonlinear dynamic system. The variation in the mass of the beater link influences the performance of the system considerable especially at mass range below 0.06 kg during which chaotic behavior of the follower link is observed. However to avoid chaotic operation of the system, the mass of the system features as considered should not be below 0.06 kg as evident in Figure 9.

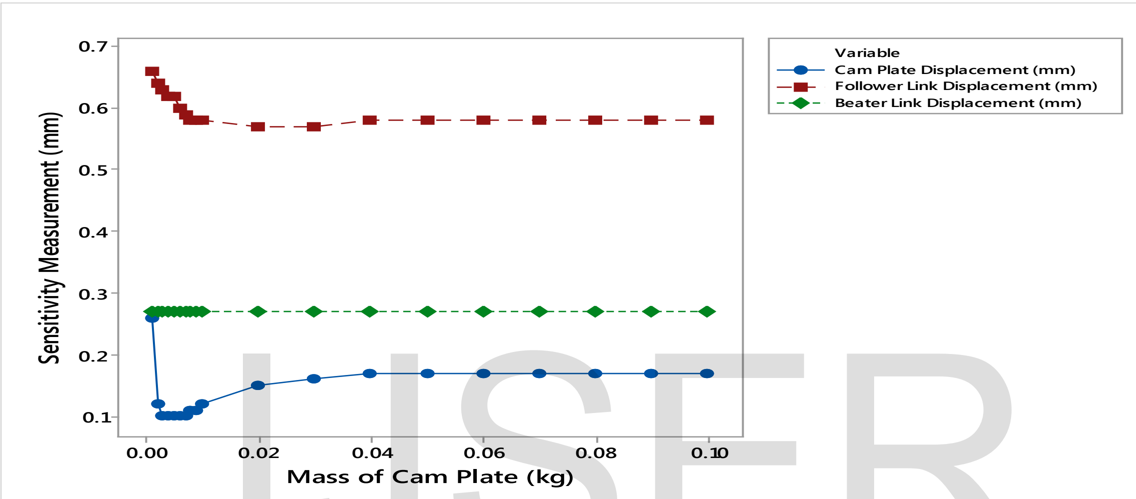


Figure 7. Sensitivity performance of nonlinear dynamic system with varying mass of cam plate

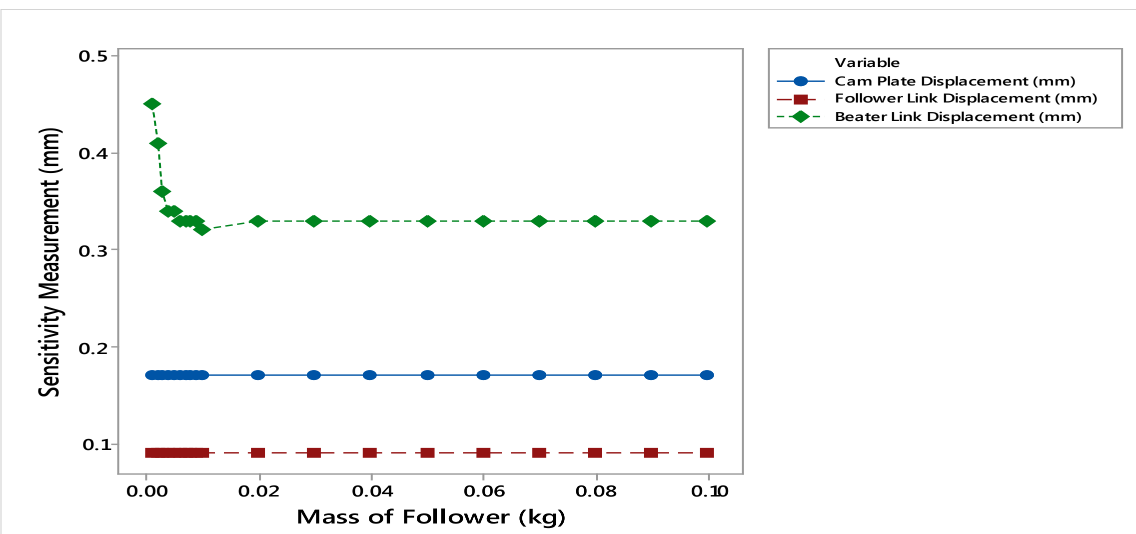


Figure 8. Sensitivity performance of nonlinear dynamic system with varying mass of follower link

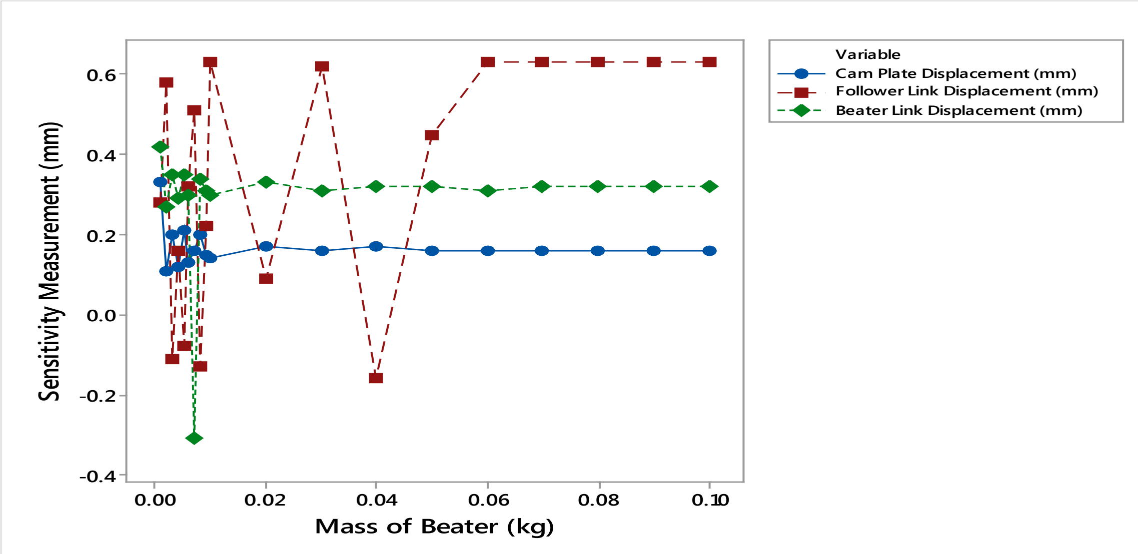


Figure 9. Sensitivity performance of nonlinear dynamic system with varying mass of beater link

Careful selection of materials for the fabrication of the system may be required for the design of the follower link and designers should lay emphasize on this. It is desired to minimize the total mass of the system for optima operation as often obtained in the design of cam follower system, therefore active control towards eliminating the chaotic behavior of the follower link may be applied based on feedback approach in which the difference between the output signal from the follower link is compared with the input signal of the system and the difference fed into a compensator for the regulation of the follower output for desired operation.

4. Conclusion

In this paper the performance sensitivity of a cam swing roller follower system for the design of beat-up motion in narrow loom weaving machine was investigated. The complex system model equations were developed for the system vibration and performance responses using Newton's second law of motion. The models were used to simulate the system operation using SIMULINK in MATLAB application. Partial sensitivity analysis were carried out to obtain the sensitivity values of the cam plate, follower link and beater link of the system. The system performance was observed to be influenced by the variation in the inertia parameters such as the masses of the cam plate, follower link and beater link setting a limit for the selection of inertia parameters for the design of the cam follower system for smooth operation.

References

Alaci, Stelian, Florina Carmen Cionei, Dumitru Amarandei, Constantin Filote, Simion Pătraş-Ciceu, and Dorel Prodan. "SOME ASPECTS REGARDING COMPUTER AIDED DESIGN OF CAM MECHANISMS WITH FLAT FACE OSCILLATING FOLLOWER." *Fiability & Durability* 1, no. 7 (2011): 65-70.

Andrisano, A.O., M. Ansaloni, F. Leali, M. Pellicciari, and A. Vergnano. "A novel method for sensitivity analysis and characterization in integrated engineering design." *International conference on Innovative Methods in Product Design.* Venice, Italy, 2011. 272-279.

Castillo, C., R. Mı´nguez, E. Castillo, and M.A. Losada. "An optimal engineering design method with failure rate constraints and sensitivity analysis. Application to composite breakwaters." *Coastal Engineering* (Elsivier) 53 (2006): 1-25.

Chablat, D., and J. Angeles. "Strategies for the design of a slide-o-cam transmission." *Proceedings of CK2005, International Workshop on Computational Kinematics.* Ecole Centrale de Nantes, 2005. 1-20.

Chang, Wen-Tung, and Long-Iong Wu. "A computerized approach for tolerance analysis of disk cam mechanisms with a flat-faced follower." *Transactions of the Canadian Society for Mechanical Engineering* 33, no. 3 (2009): 459-485.

Chang, Wen-Tung, and Long-Iong Wu. "Computerized tolerance analysis of disk cam mechanisms with a roller follower." *Engineering with Computers* 25 (2009b): 247-260.

Deihimi, A. "Design Optimization of Switched Reluctance Machines for Maximum Torque/Current using BEM-Based Sensitivity Analysis." *International Journal of Recent Trends in Engineering* 2, no. 5 (2009): 167-173.

Demeulenaere, B., and J. De Schutter. "Accurate Realization of Follower Motions in High-Speed Cam-Follower Mechanisms." *Proceedings of ISMA.* 2002. 1107-1116.

Demeulenaere, Bram, Pieter Spaepen, and Joris De Schutter. "Input Torque Balancing Using a Cam-Based Centrifugal Pendulum: Design Procedure and Example." *Journal of sound and vibration* 283 (2005): 1-20.

Dickrell-III, D. J., D. B. Dooner, and W. G. Sawyer. "The Evolution of Geometry for a Wearing Circular Cam: Analytical and Computer Simulation With Comparison to Experiment." *Journal of Tribology* 125 (2003): 187-192.

Ebrahimi, Saeed, and Jozesef Kövecses. "Sensitivity analysis for estimation of inertial parameters of multibody mechanical systems." *Mechanical Systems and Signal Processing* (Elsivier) 24 (2010): 19-28.

Farhat, N., M.-A. Díaz, and V. Mata. "Dynamic Parameter Identification of Parallel Robots Considering Physical Feasibility and Nonlinear Friction Models." *12th IFToMM World Congress.* Besançon (France), 2007. p. 6.

Flores, Paulo. "A Computational Approach for Cam Size Optimization of Disc Cam-Follower Mechanisms With Translating Roller Followers." *Journal of Mechanisms and Robotics* 5 (2013): 041010-1-6.

Gatti, Gianluca, and Domenico Mundo. "On the direct control of follower vibrations in cam–follower mechanisms." *Mechanism and Machine Theory* 45 (2010): 23-35.

Gholami, Farnood, József Kövecses, and Josep M. Font-Llagunes. "Parametric analysis of impact configurations in crutch walking." Edited by J.C. Samin and P. Fisette. *MULTIBODY DYNAMICS 2011, ECCOMAS Thematic Conference.* Brussels, Belgium, 2011. p. 7.

Hajžman, Michal, and Pavel Polach. "Sensitivity analysis of gearbox torsional vibrations." *Engineering MECHANICS* 19, no. 2/3 (2012): 77-86.

Hsieh, Jung-Fa. "Design and analysis of offset slider-crank with translating roller follower ." *Transactions of the Canadian Society for Mechanical Engineering* 35, no. 3 (2011): 419-436.

Hu, Bo, Changjiang Zhou, and Lin Ma. "Dynamics model of a cam mechanism with an elastic oscillating roller follower." *The 14th IFToMM World Congress.* Taipei, Taiwan, 2015. 1-5.

Huang, Chih-Yung, Cheng-Kang Hu, Chih-Jie Yu, and Cheng-Kuo Sung. "Experimental Investigation on the Performance of a Compressed-Air Driven Piston Engine." *Energies*, 2013: 1731-1745.

Jing, Sun, and Yao Yan-An. "An independent active torque balancer using a servo-controlled differential gear train." *Transactions of the Canadian Society for Mechanical Engineering* 33, no. 2 (2009): 329-348.

Kaplan, Halit. "Mathematical modeling and simulation of high-speed cam mechanisms to minimize residual vibrations." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science.* Institution of Mechanical Engineers, 2014. 2402–2415.

Kinsheel, Azeddien, Zahari Taha, Abdelhakim Deboucha, and Tuan Mohd Yusoff Shah Tuan Ya. "Robust least square estimation of the CRS A465 robot arm’s dynamic model parameters." *Journal of Mechanical Engineering Research* 4, no. 3 (2012): 89-99.

Kirana, Tushar, and S. K. Srivastavab. "Analysis and Simulation of Cam Follower Mechanism Using Polynomial Cam Profile." *International Journal of Multidisciplinary and Current Research*, 2013: 211-215.

Kloepper, Robert, Hiroto Akita, Masaaki Okuma, and Seiichi Terada. "An Experimental Identification Method for Rigid Body Properties Enabled by Gravity-Dependent Suspension Modelling." *The 1st Joint International Conference on Multibody System Dynamics .* Lappeenranta, Finland, 2010. p. 9.

Kolansky, Jeremy, and Corina Sandu. "Real-time parameter estimation study for inertia properties of ground vehicles." *The Achive of Mechanical Engineering* LX, no. 1 (2013): p. 15.

Kuang, Jao-Hwa, and Chao-Ming Hsu. "Dynamic Behavior of Roller Gear Cam Systems with Different Torque Compensation Mechanisms." *12th IFToMM World Congress.* Besançon (France), 2007.

Lahr, Derek F., and Dennis W. Hong. "Contact stress reduction mechanisms for the cam-based infinitely variable transmission." *Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference.* Las Vegas, Nevada, USA: ASME, 2007. 1-8.

Lei, Li, and Zhang Jianrun. "Multidisciplinary Design Optimization of Distribution Cam Mechanism of Diesel Engine." *Applied Mathematics & Information Sciences* 7, no. 5 (2013): 1957-1962.

Lovasz, E.-C., D. Perju, C. M. Gruescu, K.-H. Modler, and Caˇraˇbas I. "Numerical Method for Determination of Base Circle Radius of Cam Mechanisms with Oscillating Flat-Face Follower." *Advances in Mechanisms Design, Mechanisms and Machine Science* 8 (2012): 143-149.

Lovasz, E.C., D. Perju, K.H. Modler, C.M. Gruescu, I. Maniu, and E.S. Zabava. "Numerical Iterative Method for Computing the Base Circle Radius of Cam Mechanisms with Translating Flat-Face Follower."

New Trends in Mechanism and Machine Science Mechanisms and Machine Science 7 (2013): 237-244.

Müller, O., A. Albers, B. Ilzhöfer, and P. Häußler. "Multidisciplinary shape and topology optimization and its integration in the product design process for the effective development of competitive products." *INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN.* Munich, 1999. p. 6.

Neto, Maria Augusta, Jorge A. C. Ambr´osio, and Rog´erio Pereira Leal. "Sensitivity analysis of flexible multibody systems using composite materials components." *International Journal for Numerical Methods in Engineering* (John Wiley & Sons, Ltd), 2008: p. 28.

Nguyen, Vu-Thinh, and Dojoong Kim. "CAM PROFILE SMOOTHING BY MODIFIED SPLINE CURVES." *12th IFToMM World Congress, June 18-21.* Besançon (France), 2007. 1-6.

Patel, N.S. "Modelling, Design and Analysis of Cam and Follower- A Review Paper." *International Journal of Engineering Studies and Technical Approach* 1, no. 2 (2015): 37-42.

Pourghodrat, Abolfazl, and Carl A. Nelson. "A case study of designing a cam-follower mechanism with cycloidal motion." *13th World Congress in Mechanism and Machine Science.* Guanajuato, México, 2011. 1-7.

Raji, N. A, and P. A. O Adegbuyi. "Synthesis of Cam Follower System for the Beater Mechanism of a Narrow Horizontal Loom." *Nigerian Journal of Mechanical Engineering* 1, no. 1 (2003): 37-48.

Raji, N.A, A.A Erameh, F.O Ajayi, and R.O Kuku. "Impact Analysis of Narrow Loom Beat-up Mechanism." *Research Journal of Applied Sciences, Engineering and Technology* 3, no. 9 (2011): 923-927.

Raji, N.A, A.A Erameh, V.O Ozor, F.O Ajayi, and R.O Kuku. "Modeling Narrow loom Beat-up System with Cam Transmission Influence." *Journal of Engineering and Applied Sciences* 5, no. 3 (2010): 206-210.

Raji, Nurudeen A. "Motion Specification for Beat-Up Mechanism of Narrow Horizontal weaving Loom. Annals of Engineering Analysis." *Annals of Engineering Analysis* 1, no. 2 (2000): 28-40.

Realmuto, Jonathan, Glenn Klute, and Santosh Devasia. "Nonlinear Passive Cam-Based Springs for Powered Ankle Prostheses." *Journal of Medical Devices*, 2015: 1-10.

Sateesh, N. "IMPROVEMENT IN MOTION CHARACTERISTICS OF CAM-FOLLOWER SYSTEMS USING NURBS." *International Journal on Design & Manufacturing Technologies* 8, no. 2 (2014): 15-21.

Serban, Radu, and Linda R. Petzold. "Efficient computation of sensitivities for ordinary differential equation boundary value problems." *SIAM Journal of Numerical Analysis* (Society for Industrial and Applied Mathematics) 40, no. 1 (2002): 220–232.

Singh, P K, S C Jain, and P K Jain. "A genetic algorithm based solution to optimum tolerance synthesis of mechanical assemblies with alternate manufacturing processes—benchmarking with the exhaustive search method using the Lagrange multiplier." *Proceedings of the Institution of Mechanical Engineers.* Journal of Engineering Manufacture, 2004. 765-778.

Stephens, D.W., D. Gorissen, and T. Dhaene. "Surrogate based sensitivity analysis of process equipment." *Seventh International Conference on CFD in the Minerals and Process Industries.* Melbourne, Australia, 2009. p. 9.

Sun, Jianping, and Yiping Luo. "The Parametric Design and Motion Analysis of Disc Cam Mechanism with Straight Motion and Deviation Roller Follower." *Applied Mechanics and Materials* 26-28 (2010): 360-364.

Thai, Huynh Le Hong, and Jaroslav Beran. "Sensitivity analysis and optimization the needle of knitting machine by stress constraint." *7th International Conference.* Liberec, Czech Republic, 2010.

Tounsi, M., F. Chaari, L. Walha, T. Fakhfakh, and M. Haddar. "Dynamic behavior of a valve train system in presence of camshaft errors." *WSEAS TRANSACTIONS on APPLIED and THEORETICAL MECHANICS* 1, no. 6 (2011): 17-26.

Trabelsi, Hassen, Fakher Chaâri, and Mohamed Haddar. "Influence of cam profile errors on the dynamic behavior of a cam follower system." *19th International congress on acoustics.* Madrid, 2007. 1-7.

Tsiafis, I., S. Mitsi, K.D. Bouzakis, and A. Papadimitriou. "Optimal Design of a Cam Mechanism with Translating Flat-Face Follower using Genetic Algorithm." *Tribology in Industry*, 2013: 255-260.

Wang, Linyan, Tao Shen, Yunbo Shen, and Shaokang Li. "Development of Parametric Design System for Disc Cams with Translating Roller Followers." *Advanced Materials Research* 411 (2012): 83-87.

Wolf, Susann, Joachim Haase, and Christoph Clauß. "Methods of Sensitivity Calculation Applied to a Multi-Axial Test Rig for Elastomer Bushings." *The Modelica Association*, 2008: 521-529.

Wu, Long-Iong, Wen-Tung Chang, and Chun-Hsien Liu. "The design of varying-velocity translating cam mechanisms." *Mechanism and Machine Theory* 42, no. 3 (2007): 352-364.

Xiang, Yujiang, Jasbir S. Arora, and Karim Abdel-Malek. "Optimization-based motion prediction of mechanical systems: sensitivity analysis." *Struct Multidisc Optim* (Springer-Verlag), 2008: 1-14.

Xiao, Hansong, and Jean W. Zu. "Cam profile optimization for a new cam drive." *Journal of Mechanical Science and Technology* 23 (2009): 2592~2602.

Yu, Q., and H. P Lee. "Size optimization of cam mechanisms with translating roller followers." *Proc Instn Mech Engrs* 212 (1998): 381-385.

Zhang, C., and H.-P. Ben Wang. "Tolerance analysis and synthesis for cam mechanisms." *International Journal of Production Research* 31, no. 5 (1993): 1229-1245.