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Gait Analysis of Quadruped Robot Using the Equivalent Mechanism Concept Based on Metamorphosis

Kun Xu, Peijin Zi and Xilun Ding

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Review

(2019)32:15

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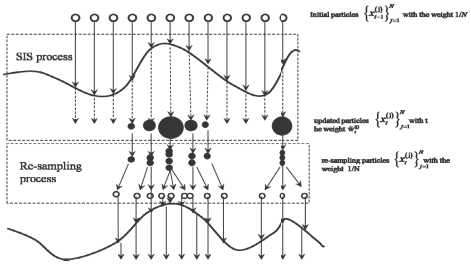
Remaining Useful Life Model and Assessment of Mechanical Products: A Brief Review and a Note on the State Space Model Method.

Yawei Hu • Shujie Liu • Huitian Lu • Hongchao Zhang

Abstract: The remaining useful life (RUL) prediction of mechanical products has been widely studied for online system performance reliability, device remanufacturing, and product safety (safety awareness and safety improvement). These studies incorporated many different models, algorithms, and techniques for modeling and assessment. In this paper, methods of RUL assessment are summarized and expounded upon using two major methods: physical model based and data driven based methods. The advantages and disadvantages of each of these methods are deliberated and compared as well. Due to the intricacy of failure mechanism in system, and difficulty in physical degradation observation, RUL assessment based on observations of performance variables turns into a science in evaluating the degradation. A modeling method from control systems, the state space model (SSM), as a first order hidden Markov, is presented. In the context of non-linear and non-Gaussian systems, the SSM methodology is capable of performing remaining life assessment by using Bayesian estimation (sequential Monte Carlo). Being effective for non-linear and non-Gaussian dynamics, the methodology can perform the assessment recursively online for applications in CBM (condition based maintenance), PHM (prognostics and health management), remanufacturing, and system performance reliability. Finally, the discussion raises concerns regarding online sensing data for SSM modeling and assessment of RUL.



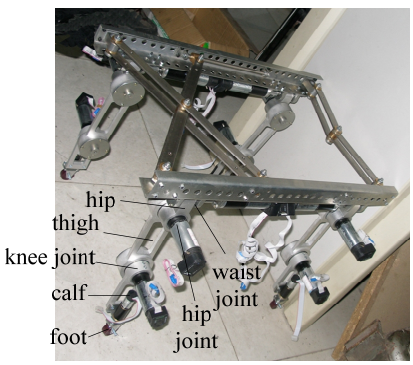
Mechanism and Robotics

(2019)32:8

DOI: 10.1186/s10033-019-0321-2

Gait Analysis of Quadruped Robot Using the Equivalent Mechanism Concept Based on Metamorphosis. Kun Xu • Peijin Zi • Xilun Ding

Abstract: The previous research regarding the gait planning of quadruped robot focuses on the sequence for lifting off and placing the feet, but neglects the influence of body height. However, body height affects gait performance significantly, such as in terms of the stride length and stability margin. We herein study the performance of a quadruped robot using the equivalent mechanism concept based on metamorphosis. Assuming the constraints between standing feet and the ground with hinges, the ground, standing legs and robot body are considered as a parallel mechanism, and each swing leg is regarded as a typical serial manipulator. The equivalent mechanism varies while the robot moves on the ground. One gait cycle is divided into several periods, including step forward stages and switching stages. There exists a specific equivalent mechanism corresponding to each gait period. The robot's locomotion can be regarded as the motion of these series of equivalent mechanisms. The kinematics model and simplified model of the equivalent mechanism is established. A new definition of the multilegged robot stability margin, based on friction coefficient, is presented to evaluate the robot stability. The stable workspaces of the equivalent mechanism in the step forward stage of trotting gait under different friction coefficients are analyzed. The stride length of the robots is presented by analyzing the relationship between the stable workspaces of the equivalent mechanisms of two adjacent step forward stages in one gait cycle. The simulation results show that the stride length is larger with increasing friction coefficient. We herein propose a new method based on metamorphosis, and an equivalent mechanism to analyze the stability margin and stable workspace of the multilegged robot.



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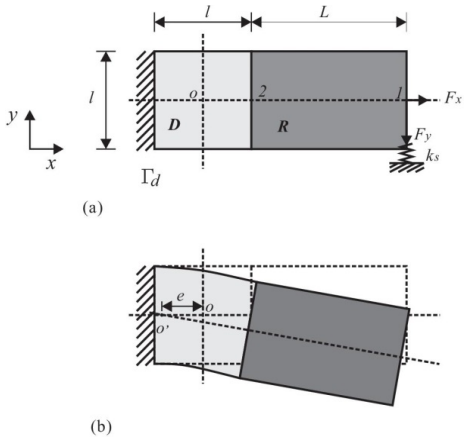


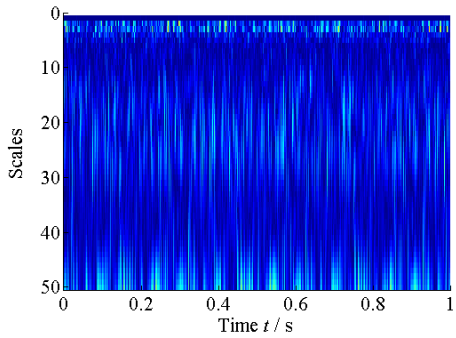
(2019)32:13
DOI: 10.1186/s10033-019-0332-z

Topological and Shape Optimization of Flexure Hinges for Designing Compliant Mechanisms Using the Level Set Method.

Benliang Zhu • Xianmin Zhang • Min Liu • Qi Chen • Hai Li

Abstract: A flexure hinge is a major component in designing compliant mechanisms that offers unique possibilities in a wide range of application fields in which high positioning accuracy is required. Although various flexure hinges with different configurations have been successively proposed, they are often designed based on designers' experiences and inspirations. This study presents a systematic method for topological optimization of flexure hinges by using the level set method. Optimization formulations are developed by considering the functional requirements and geometrical constraints of flexure hinges. The functional requirements are first constructed by maximizing the compliance in the desired direction while minimizing the compliances in the other directions. The weighting sum method is used to construct an objective function in which a self-adjust method is used to set the weighting factors. A constraint on the symmetry of the obtained configuration is developed. Several numerical examples are presented to demonstrate the validity of the proposed method. The obtained results reveal that the design of a flexure hinge starting from the topology level can yield more choices for compliant mechanism design and obtain better designs that achieve higher performance.

Intelligent Manufacturing Technology



(2019)32:9
DOI: 10.1186/s10033-019-0324-z

Application of Instantaneous Rotational Speed to Detect Gearbox Faults Based on Double Encoders. Lin Liang • Fei Liu • Xiangwei Kong • Maolin Li • Guanghua Xu

Abstract: Considerable studies have been carried out on fault diagnosis of gears, with most of them concentrated on conventional vibration analysis. However, besides the complexity of gear dynamics, the diagnosis results in terms of vibration signal are easily misjudged owing to the interference of sensor position or other components. In this paper, an alternative gearbox fault detection method based on the instantaneous rotational speed is proposed because of its advantages over vibration analysis. Depending on the timer/counter-based method for the pulse signal of the optical encoder, the varying rotational speed can be obtained effectively. Owing to the coupling and meshing of gears in transmission, the excitations are the same for the instantaneous rotational speed of the input and output shafts. Thus, the differential signal of instantaneous rotational speeds can be adopted to eliminate the effect of the interference excitations and extract the associated feature of the localized fault effectively. With the experiments on multistage gearbox test system, the differential signal of instantaneous speeds is compared with other signals. It is proved that localized faults in the gearbox generate small angular speed fluctuations, which are measurable with an optical encoder. Using the differential signal of instantaneous speeds, the fault characteristics are extracted in the spectrum where the deterministic frequency component and its harmonics corresponding to crack fault characteristics are displayed clearly.

(2019)32:10
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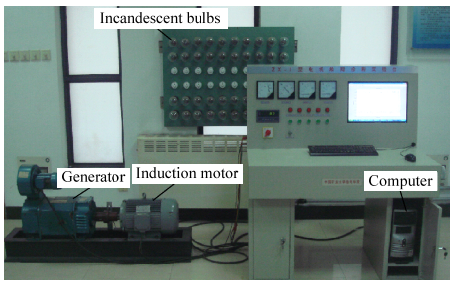
Broken Rotor Bar Fault Detection of Induction Motors Using a Joint Algorithm of Trust Region and Modified Bare-bones Particle Swarm Optimization.

Panpan Wang • Liping Shi • Yong Zhang • Yifan Wang • Li Han

Abstract: A precise detection of the fault feature parameter of motor current is a new research hotspot in the broken rotor bar (BRB) fault diagnosis of induction motors. Discrete Fourier transform (DFT) is the most popular technique in this field, owing to low computation and easy realization. However, its accuracy is often limited by the data window length, spectral leakage, fence effect, etc. Therefore, a new detection method based on a global optimization algorithm is proposed. First, a BRB fault current model and a residual error function are designed to transform the fault parameter detection problem into a nonlinear least-square problem. Because this optimization problem has a great number of local optima and needs to be resolved rapidly and accurately, a joint algorithm (called TR-MBPSO) based on a modified bare-bones particle swarm optimization (BPSO) and trust region (TR) is subsequently proposed. In the TR-MBPSO, a reinitialization strategy of inactive particle is introduced to the BPSO to enhance the swarm diversity and global search ability. Meanwhile, the TR is combined with the modified BPSO to improve convergence speed and accuracy. It also includes a global convergence analysis, whose result proves that the TR-MBPSO can converge to the global optimum with the probability of 1. Both simulations and experiments are conducted, and the results indicate that the proposed detection method not only has high accuracy of parameter estimation with short-time data window, e.g., the magnitude and frequency precision of the fault-related components reaches 10^{-4}, but also overcomes the impacts of spectral leakage and non-integer-period sampling. The proposed research provides a new BRB detection method, which has enough precision to extract the parameters of the fault feature components.

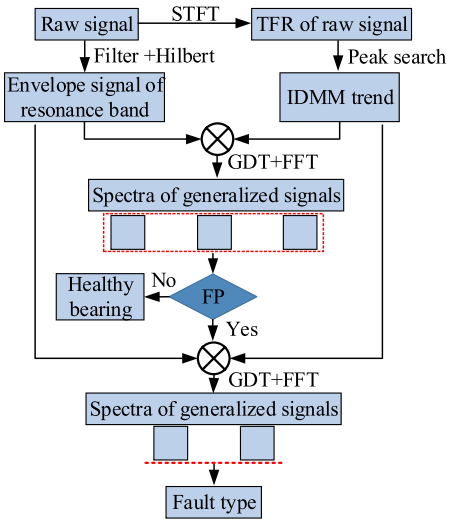


(2019)32:7
DOI: 10.1186/s10033-019-0322-1

Generalized Demodulation Transform for Bearing Fault Diagnosis Under Nonstationary Conditions and Gear Noise Interferences.

Dezun Zhao • Jianyong Li • Weidong Cheng • Zhiyang He

Abstract: It is a challenging issue to detect bearing fault under nonstationary conditions and gear noise interferences. Meanwhile, the application of the traditional methods is limited by their deficiencies in the aspect of computational accuracy and efficiency, or dependence on the tachometer. Hence, a new fault diagnosis strategy is proposed to remove gear interferences and spectrum smearing phenomenon without the tachometer and angular resampling technique. In this method, the instantaneous dominant meshing multiple (IDMM) is firstly extracted from the time-frequency representation (TFR) of the raw signal, which can be used to calculate the phase functions (PF) and the frequency points (FP). Next, the resonance frequency band excited by the faulty bearing is obtained by the band-pass filter. Furthermore, based on the PFs, the generalized demodulation transform (GDT) is applied to the envelope of the filtered signal. Finally, the target bearing is diagnosed by matching the peaks in the spectra of demodulated signals with the theoretical FPs. The analysis results of simulated and experimental signal demonstrate that the proposed method is an effective and reliable tool for bearing fault diagnosis without the tachometer and the angular resampling.



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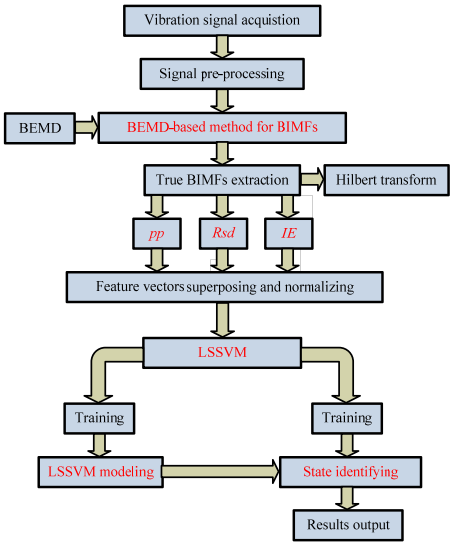
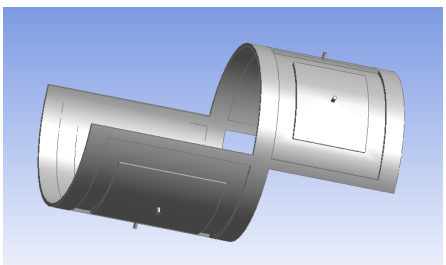


(2019)32:1

DOI: 10.1186/s10033-018-0313-7

Grinding Chatter Detection and Identification Based on BEMD and LSSVM. Huan-Guo Chen • Jian-Yang Shen • Wen-Hua Chen • Chun-Shao Huang • Yong-Yu Yi • Jia-Cheng Qian

Abstract: Grinding chatter is a self-induced vibration which is unfavorable to precision machining processes. This paper proposes a forecasting method for grinding state identification based on bivarition empirical mode decomposition (BEMD) and least squares support vector machine (LSSVM), which allows the monitoring of grinding chatter over time. BEMD is a promising technique in signal processing research which involves the decomposition of two-dimensional signals into a series of bivarition intrinsic mode functions (BIMFs). BEMD and the extraction criterion of its true BIMFs are investigated by processing a complex-value simulation chatter signal. Then the feature vectors which are employed as an amplification for the chatter premonition are discussed. Furthermore, the methodology is tested and validated by experimental data collected from a CNC guideway grinder KD4020X16 in Hangzhou Hangji Machine Tool Co., Ltd. The results illustrate that the BEMD is a superior method in terms of processing non-stationary and nonlinear signals. Meanwhile, the peak to peak, real-time standard deviation and instantaneous energy are proven to be effective feature vectors which reflect the different grinding states. Finally, a LSSVM model is established for grinding status classification based on feature vectors, giving a prediction accuracy rate of 96%.



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DOI: 10.1186/s10033-019-0326-x

Structural Design and Dynamic Characteristics of Overloaded Horizontal Servo Cylinder for Resisting Dynamic Partial Load. Linan Ma • Qingxue Huang • Lifeng Ma • Qiangjun Ma • Wenze Zhang • Heyong Han

Abstract: When an output curve force is applied to a horizontal servo cylinder with a heavy load, the piston rod bears a dynamic partial load based on the installation and load characteristics, which significantly affects the frequency response and control accuracy of the servo cylinder. Based on this partial load, increased friction can lead to cylinder bore scuffing, leakage, lack of output power, or even system failure. In this paper, a novel asymmetric static-pressure support structure is proposed based on the principle of hydrostatic support. The radial component force of a dynamic partial load is balanced by cooperation between the support oil cushion of the variable hydraulic pressure support structure, oil cushion of the supportive force, and the damper. Adaptive control of the servo cylinder piston rod, guide sleeve, and piston, as well as the cylinder oil film friction between lubricated surfaces is achieved. In this paper, theoretical design and analysis of the traditional hydrostatic bearing structure and novel structure are presented. A hydraulic dynamic shear scissor is used as a research target to derive a structural dynamic model. Comparative simulations are performed using Matlab Simulink. Additionally, flow field analysis of the novel structure is performed, which verifies the rationality and feasibility of the proposed structure and system.

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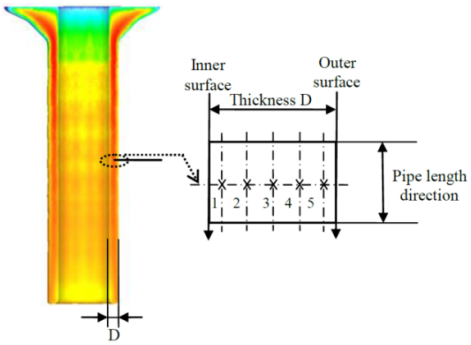
Numerical Simulation and Experimental Research on Microstructural Evolution During Compact Hot Extrusion of Heavy Caliber Thick-Wall pipe.
Lu Jia • Yongtang Li • Tianjing Hui • Yang Zhang

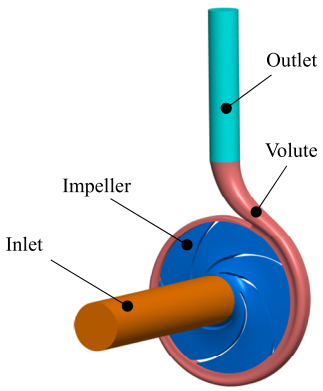
Abstract: Compact hot extrusion (CHE) process of heavy caliber thick-wall pipe is a new material-saving production process. In order to reveal the optimum hot extrusion parameters in CHE process, the effects of the extrusion parameters on the microstructural evolution are investigated systematically. The metadynamic recrystallization (MDRX) kinetic models and grain size models of as-cast P91 steel are established for the first time according to the hot compression tests performed on the Gleeble-3500 thermal-simulation machine. Then a thermal-mechanical and micro-macro coupled hot extrusion finite element (FE) model is established and further developed in DEFORM software. The results indicated that the grain size of the extruded pipe increases with the increasing of initial temperature and extrusion speed, decreases when extrusion ratio increases. Moreover, the grain size is more sensitive to the initial temperature and the extrusion ratio. The optimum hot extrusion parameters are including that, the initial extrusion temperature of 1250 ℃, the extrusion ratio of 9 and the extrusion speed of 50 mm/s. Furthermore, in order to verify the simulation precisions, hot extrusion experiment verification on the heavy caliber thick-wall pipe is carried out on the 500 MN vertical hot extrusion equipment. The load-displacement curve of the extrusion process and the grain sizes of the middle part extruded pipe are in good accuracy with the simulation results, which confirms that the hot extrusion FE models of as-cast P91 steel could estimate the hot extrusion behaviors. The proposed hot extrusion FE model can be used to guide the industrial production research of CHE process.



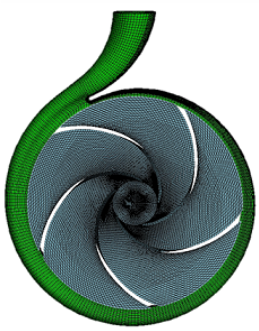
(2019)32:17
DOI: 10.1186/s10033-019-0328-8

Unsteady Flow and Structural Behaviors of Centrifugal Pump under Cavitation Conditions. Denghao Wu • Yun Ren • Jiegang Mou • Yunqing Gu • Lanfang Jiang

Abstract: Cavitation has a significant effect on the flow fields and structural behaviors of a centrifugal pump. In this study, the unsteady flow and structural behaviors of a centrifugal pump are investigated numerically under different cavitation conditions. A strong two-way coupling fluid-structure interaction simulation is applied to obtain interior views of the effects of cavitating bubbles on the flow and structural dynamics of a pump. The renormalization-group *k*-*ε* turbulence model and the Zwart-Gerber-Belamri cavitation model are solved for the fluid side, while a transient structural dynamic analysis is employed for the structure side. The different cavitation states are mapped in the head-net positive suction head (*H*-NPSH) curves and flow field features inside the impeller are fully revealed. Results indicate that cavitating bubbles grow and expand rapidly with decreasing NPSH. In addition, the pressure fluctuations, both in the impeller and volute, are quantitatively analyzed and associated with the cavitation states. It is shown that influence of the cavitation on the flow field is critical, specifically in the super-cavitation state. The effect of cavitation on the unsteady radial force and blade loads is also discussed. The results indicate that the averaged radial force increased from 8.5 N to 54.4 N in the transition progress from an onset cavitation state to a super-cavitation state. Furthermore, the structural behaviors, including blade deformation, stress, and natural frequencies, corresponding to the cavitation states are discussed. A large volume of cavitating bubbles weakens the fluid forces on the blade and decreases the natural frequencies of the rotor system. This study could enhance the understanding of the effects of cavitation on pump flow and structural behaviors.



a Fluid domains



b Meshes for fluid calculation

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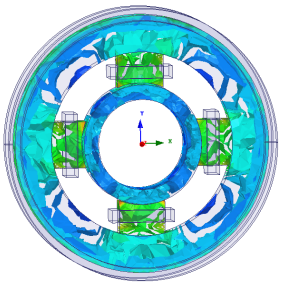
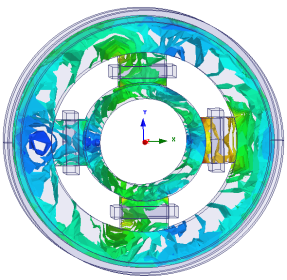


(a) The value of *i* is zero



(b) The value of *i* is maximum

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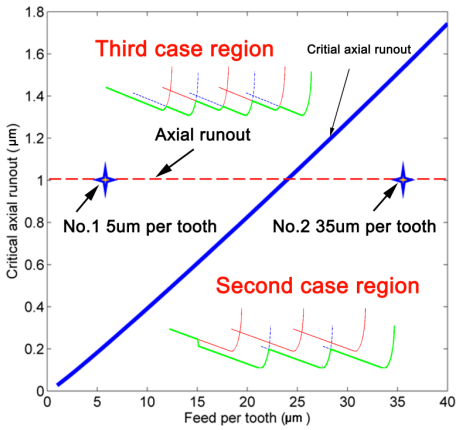
DOI: 10.1186/s10033-019-0320-3

Design and Analysis of a Magnetic Bearings with Three Degrees of Freedom.

Ye Yuan • Yukun Sun • Qianwen Xiang

Abstract: The current research of supporting and transmission system in flywheel energy storage system (FESS) focuses on the low consumption design. However, friction loss is a non-negligible factor in the high-speed but lightweight FESS energy and momentum storage with mechanical-type supporting system. In order to realize the support system without mechanical loss and to maximize the efficiency of the flywheel battery, a permanent magnet biased magnetic bearings (PMBMB) is applied to the FESS with the advantages of low loss, high critical speed, flexible controllability and compact structure. In this frame, the relevant research of three degrees of freedom (3-DOF) PMBMB for a new type FESS is carried out around the working principle, structural composition, coupling characteristics analysis, mathematical model, and structural design. In order to verify the performance of the 3-DOF PMBMB, the radial force mathematical model and the coupling determination equations of radial two DOF are calculated according to an equivalent magnetic circuit, and radial-axial coupling is analyzed through finite element analysis. Moreover, a control system is presented to solve the control problems in practical applications. The rotor returns to the balanced position in 0.05 s and maintains stable suspension. The displacement fluctuation is approximately 40 μm in the *y* direction and 30 μm in the *x* direction. Test results indicate that the dynamic rotor of the proposed flywheel energy storage system with PMBMB has excellent characteristics, such as good start-of-suspension performance and stable suspension characteristics. The proposed research provides the instruction to design and control a low loss support system for FESS.



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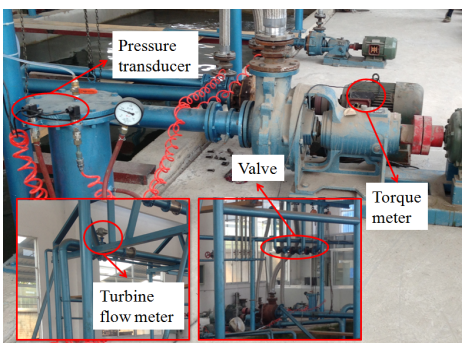
DOI: 10.1186/s10033-019-0318-x

Modelling of the Influence of Tool Runout on Surface Generation in Micro Milling.

Wanqun Chen • Yazhou Sun • Dehong Huo • Xiangyu Teng

Abstract: Micro milling is a flexible and economical method to fabricate micro components with three-dimensional geometry features over a wide range of engineering materials. But the surface roughness and micro topography always limit the performance of the machined micro components. This paper presents a surface generation simulation in micro end milling considering both axial and radial tool runout. Firstly, a surface generation model is established based on the geometry of micro milling cutter. Secondly, the influence of the runout in axial and radial directions on the surface generation are investigated and the surface roughness prediction is realized. It is found that the axial runout has a significant influence on the surface topography generation. Furthermore, the influence of axial runout on the surface micro topography was studied quantitatively, and a critical axial runout is given for variable feed per tooth to generate specific surface topography. Finally, the proposed model is validated by means of experiments and a good correlation is obtained. The proposed surface generation model offers a basis for designing and optimizing surface parameters of functional machined surfaces.



(2019)32:4

DOI: 10.1186/s10033-019-0319-9

Influence of Cross-Sectional Flow Area of Annular Volute Casing on Transient Characteristics of Ceramic Centrifugal Pump.

Yi Tao • Shouqi Yuan • Jianrui Liu • Fan Zhang

Abstract: The annular volute is typically used in a slurry pump to reduce the collisions between solid particles and the volute tongue and to achieve a better resistance to blocking. However, only limited studies regarding annular volutes are available, and there is no systematic design method for annular volutes. In this study, the influence of volute casing cross-sectional flow area on the hydraulic loss, pressure pulsations, and radial force under varying working conditions in a centrifugal ceramic pump are discussed in detail. Experimental tests were conducted to validate the numerical results. The results indicated that, when the volute casing flow area increases, the hydraulic performance decreases marginally under the rated working conditions, but increases at the off-design points, specifically under large flow condition. However, the volute casing with a larger flow area has a wider high-efficiency region. In addition, the increase in the volute casing flow area will decrease the pressure pulsations in the volute, regardless of the working condition, and decrease the radial force on the shaft, therefore, providing an improved pump operational stability. It is anticipated that this study will be of benefit during the design of annular volutes.

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Advanced Transportation Equipment

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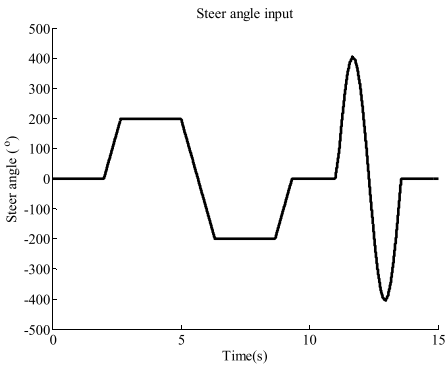
A Novel Integrated Stability Control Based on Differential Braking and Active Steering for Four-axle Trucks. Buyang Zhang • Changfu Zong • Guoying Chen • Yanjun Huang • Ting Xu

Abstract: Differential braking and active steering have already been integrated to overcome their shortcomings. However, existing research mainly focuses on two-axle vehicles and controllers are mostly designed to use one control method to improve the other. Moreover, many experiments are needed to improve the robustness; therefore, these control methods are underutilized. This paper proposes an integrated control system specially designed for multi-axle vehicles, in which the desired lateral force and yaw moment of vehicles are determined by the sliding mode control algorithm. The output of the sliding mode control is distributed to the suitable wheels based on the abilities and potentials of the two control methods. Moreover, in this method, fewer experiments are needed, and the robustness and simultaneity are both guaranteed. To simplify the optimization system and to improve the computation speed, seven simple optimization subsystems are designed for the determination of control outputs on each wheel. The simulation results show that the proposed controller obviously enhances the stability of multi-axle trucks. The system improves 68% of the safe velocity, and its performance is much better than both differential braking and active steering. This research proposes an integrated control system that can simultaneously invoke differential braking and active steering of multi-axle vehicles to fully utilize the abilities and potentials of the two control methods.



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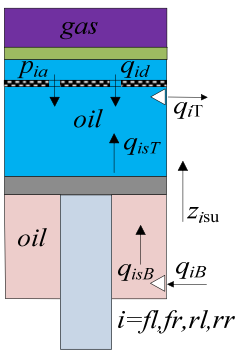
DOI: 10.1186/s10033-019-0315-0

Vibration Performance Analysis of a Mining Vehicle with Bounce and Pitch Tuned Hydraulically Interconnected Suspension. Jie Zhang • Yuanwang Deng • Nong Zhang • Bangji Zhang • Hengmin Qi • Minyi Zheng

Abstract: The current investigations primarily focus on using advanced suspensions to overcome the tradeoff design of ride comfort and handling performance for mining vehicles. It is generally realized by adjusting spring stiffness or damping parameters through active control methods. However, some drawbacks regarding control complexity and uncertain reliability are inevitable for these advanced suspensions. Herein, a novel passive hydraulically interconnected suspension (HIS) system is proposed to achieve an improved ride-handling compromise of mining vehicles. A lumped-mass vehicle model involved with a mechanical–hydraulic coupled system is developed by applying the free-body diagram method. The transfer matrix method is used to derive the impedance of the hydraulic system, and the impedance is integrated to form the equation of motions for a mechanical–hydraulic coupled system. The modal analysis method is employed to obtain the free vibration transmissibilities and force vibration responses under different road excitations. A series of frequency characteristic analyses are presented to evaluate the isolation vibration performance between the mining vehicles with the proposed HIS and the conventional suspension. The analysis results prove that the proposed HIS system can effectively suppress the pitch motion of sprung mass to guarantee the handling performance, and favorably provide soft bounce stiffness to improve the ride comfort. The distribution of dynamic forces between the front and rear wheels is more reasonable, and the vibration decay rate of sprung mass is increased effectively. This research proposes a new suspension design method that can achieve the enhanced cooperative control of bounce and pitch motion modes to improve the ride comfort and handling performance of mining vehicles as an effective passive suspension system.



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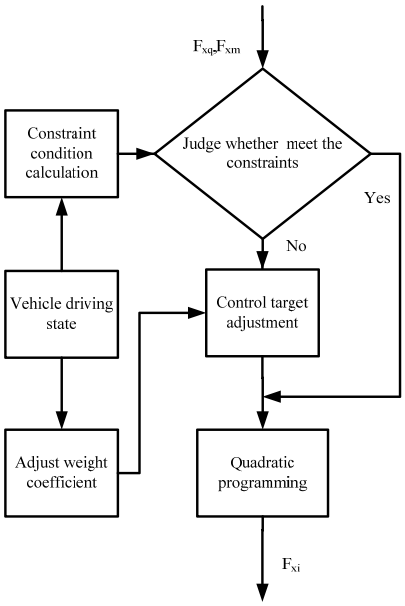

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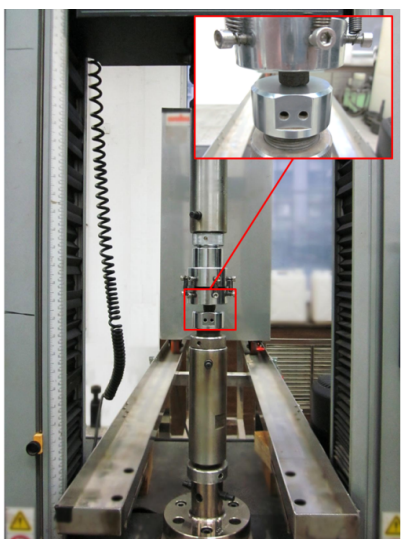
Trajectory Tracking of Autonomous Vehicle with the Fusion of DYC and Longitudinal-Lateral Control. Fen Lin • Yaowen Zhang • Youqun Zhao • Guodong Yin • Huiqi Zhang • Kaizheng Wang

Abstract: The current research of autonomous vehicle motion control mainly focuses on trajectory tracking and velocity tracking. However, numerous studies deal with trajectory tracking and velocity tracking separately, and the yaw stability is seldom considered during trajectory tracking. In this research, a combination of the longitudinal–lateral control method with the yaw stability in the trajectory tracking for autonomous vehicles is studied. Based on the vehicle dynamics, considering the longitudinal and lateral motion of the vehicle, the velocity tracking and trajectory tracking problems can be attributed to the longitudinal and lateral control. A sliding mode variable structure control method is used in the longitudinal control. The total driving force is obtained from the velocity error in order to carry out velocity tracking. A linear time-varying model predictive control method is used in the lateral control to predict the required front wheel angle for trajectory tracking. Furthermore, a combined control framework is established to control the longitudinal and lateral motions and improve the reliability of the longitudinal and lateral direction control. On this basis, the driving force of a tire is allocated reasonably by using the direct yaw moment control, which ensures good yaw stability of the vehicle when tracking the trajectory. Simulation results indicate that the proposed control strategy is good in tracking the reference velocity and trajectory and improves the performance of the stability of the vehicle.



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Safety Assessment of Aircraft Fuel Tank Access Cover under the Impact Load by Tire Fragments. Shile Yao • Zhufeng Yue • Xiaoliang Geng • Peiyan Wang

Abstract: According to relevant airworthiness standards, the aircraft fuel tank access cover must withstand the impact by tire fragments, and minimize the penetration and deformation, which is critical for flight safety. To assess the safety of an aircraft fuel tank access cover subjected to tire fragments, a study of dynamic response was presented in this paper using the Finite element (FE) software ANSYS/LS-DYNA. To obtain the reliable mechanical characteristics of tire tread rubber, a series of material tests have been conducted. Then the proposed rubber material model is validated by comparing the numerical simulations with the experimental results of aluminium alloy plate impact. The simulation results indicate that the rubber fragment and alloy plate will undergo the largest deformation when impact angle is equal to 90°. Finally, the proposed FE model and modelling approaches are extended to the numerical simulation of a full-scale aircraft fuel tank access cover impact. The numerical simulations are carried out with impact velocity of 71.1 m/s and impact angle of 40.5°. The simulation results indicate that the aluminium alloy by precision casting is more likely to rupture, and the middle region of the access cover is vulnerable to fragment impact. This research proposes a reliable rubber model applying to various strain rates. Considering the influence of impact regions, the dynamic response and various failure patterns of fuel tank access cover are acquired. The findings of this paper can be used to improve the future aircraft safety design.