

# CHINESE JOURNAL OF MECHANICAL ENGINEERING

## Mechanism and Robotics

DOI: 10.3901/CJME.2016.0413.051

- 649 **Mechanics Unloading Analysis and Experimentation of a New Type of Parallel Biomimetic Shoulder Complex.** HOU Yulei, LI Zhisen, WANG Yi, ZHANG Wenwen, ZENG Daxing, and ZHOU Yulin

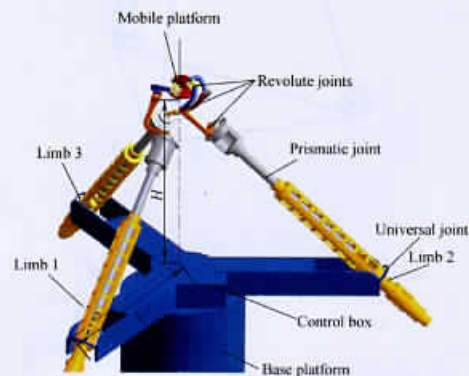
**Abstract:** The structure design for high ratio of carrying capacity to deadweight is one of the challenges for the bionic mechanism, while the problem concerning high carrying capacity has not yet been solved for the existing shoulder complex. A new type biomimetic shoulder complex, which adopts 3-PSS/S(P for prismatic pair, S for spherical pair) spherical parallel mechanism (SPM), is proposed. The static equilibrium equations of each component are established by using the vector method and the equations for constrain forces with certain load are solved. Then the constrain force on the middle limb and that on the side limbs are compared in order to verify the unloading performance of the mechanism. In addition, the prototype mechanism of the shoulder complex is developed, and the force feedback experiment is conducted to verify the static analysis, which indicates that the middle limb suffers most of the external force and the effect of mechanics unloading is achieved. The 3-PSS/S spherical parallel mechanism is presented for the shoulder complex, and the realization of mechanics unloading is benefit for the improvement of the carrying capacity of the shoulder complex.



DOI: 10.3901/CJME.2016.0121.011

- 659 **Optimal Design of a 3-Leg 6-DOF Parallel Manipulator for a Specific Workspace.** FU Jianxun, and GAO Feng

**Abstract:** Researchers seldom study optimum design of a six-degree-of-freedom (DOF) parallel manipulator with three legs based upon the given workspace. An optimal design method of a novel three-leg six-DOF parallel manipulator (TLPM) is presented. The mechanical structure of this robot is introduced, with this structure the kinematic constrain equations is decoupled. Analytical solutions of the forward kinematics are worked out, one configuration of this robot, including position and orientation of the end-effector are graphically displayed. Then, on the basis of several extreme positions of the kinematic performances, the task workspace is given. An algorithm of optimal designing is introduced to find the smallest dimensional parameters of the proposed robot. Examples illustrate the design results, and a design stability index is introduced, which ensures that the robot remains a safe distance from the boundary of its actual workspace. Finally, one prototype of the robot is developed based on this method. This method can easily find appropriate kinematic parameters that can size a robot having the smallest workspace enclosing a predefined task workspace. It improves the design efficiency, ensures that the robot has a small mechanical size possesses a large given workspace volume, and meets the lightweight design requirements.



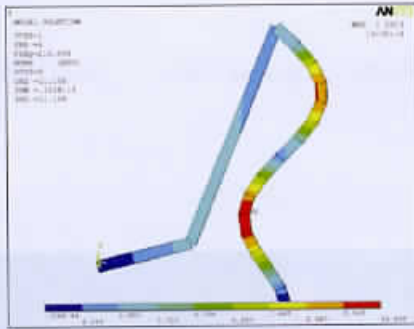
DOI: 10.3901/CJME.2016.0122.012

- 669 **Method for Six-Legged Robot Stepping on Obstacles by Indirect Force Estimation.** XU Yilin, GAO Feng, PAN Yang, and CHAI Xun

**Abstract:** Adaptive gaits for legged robots often requires force sensors installed on foot-tips, however impact, temperature or humidity can affect or even damage those sensors. Efforts have been made to realize indirect force estimation on the legged robots using leg structures based on planar mechanisms. Robot Octopus III is a six-legged robot using spatial parallel mechanism (UP-2UPS) legs. This paper proposed a novel method to realize indirect force estimation on walking robot based on a spatial parallel mechanism. The direct kinematics model and the inverse kinematics model are established. The force Jacobian matrix is derived based on the kinematics model. Thus, the indirect force estimation model is established. Then, the relation between the output torques of the three motors installed on one leg to the external force exerted on the foot tip is described. Furthermore, an adaptive tripod static gait is designed. The robot alters its leg trajectory to step on obstacles by using the proposed adaptive gait. Both the indirect force estimation model and the adaptive gait are implemented and optimized in a real time control system. An experiment is carried out to validate the indirect force estimation model. The adaptive gait is tested in another experiment. Experiment results show that the robot can successfully step on a 0.2 m-high obstacle. This paper proposes a novel method to overcome obstacles for the six-legged robot using spatial parallel mechanism legs and to avoid installing the electric force sensors in harsh environment of the robot's foot tips.

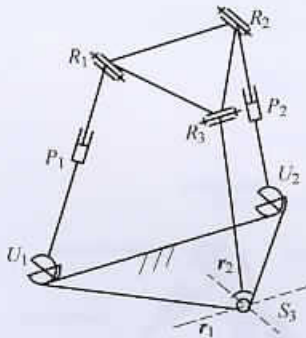


- 680 **Analysis of Frequency Characteristics and Sensitivity of Compliant Mechanisms.** LIU Shanzeng, DAI Jiansheng, LI Aimin, SUN Zhaopeng, FENG Shizhe, and CAO Guohua



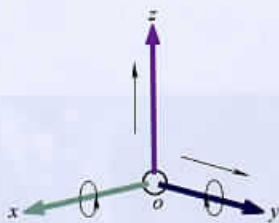
**Abstract:** Based on a modified pseudo-rigid-body model, the frequency characteristics and sensitivity of the large-deformation compliant mechanism are studied. Firstly, the pseudo-rigid-body model under the static and kinetic conditions is modified to enable the modified pseudo-rigid-body model to be more suitable for the dynamic analysis of the compliant mechanism. Subsequently, based on the modified pseudo-rigid-body model, the dynamic equations of the ordinary compliant four-bar mechanism are established using the analytical mechanics. Finally, in combination with the finite element analysis software ANSYS, the frequency characteristics and sensitivity of the compliant mechanism are analyzed by taking the compliant parallel-guiding mechanism and the compliant bistable mechanism as examples. From the simulation results, the dynamic characteristics of compliant mechanism are relatively sensitive to the structure size, section parameter, and characteristic parameter of material on mechanisms. The results could provide great theoretical significance and application values for the structural optimization of compliant mechanisms, the improvement of their dynamic properties and the expansion of their application range.

- 694 **Type Synthesis of Two-Degrees-of-Freedom Rotational Parallel Mechanism with Two Continuous Rotational Axes.** XU Yundou, ZHANG Dongsheng, WANG Min, YAO Jiantao, and ZHAO Yongsheng



**Abstract:** The two-rotational-degrees-of-freedom(2R) parallel mechanism(PM) with two continuous rotational axes(CRAs) has a simple kinematic model. It is therefore easy to implement trajectory planning, parameter calibration, and motion control, which allows for a variety of application prospects. However, no systematic analysis on structural constraints of the 2R-PM with two CRAs has been performed, and there are only a few types of 2R-PM with two CRAs. Thus, a theory regarding the type synthesis of the 2R-PM with two CRAs is systematically established. First, combining the theories of reciprocal screw and space geometry, the spatial arrangement relationships of the constraint forces applied to the moving platform by the branches are explored, which give the 2R-PM two CRAs. The different distributions of the constraint forces in each branch are also studied. On the basis of the obtained structural constraints of branches, and considering the geometric relationships of constraint forces in each branch, the appropriate kinematic chains are constructed. Through the reasonable configuration of branch kinematic chains corresponding to every structural constraint, a series of new 2R-PMs with two CRAs are finally obtained.

- 703 **Structural Synthesis of a Class of 2R2T Hybrid Mechanisms.** TIAN Chunxu, FANG Yuefa, and GUO Sheng

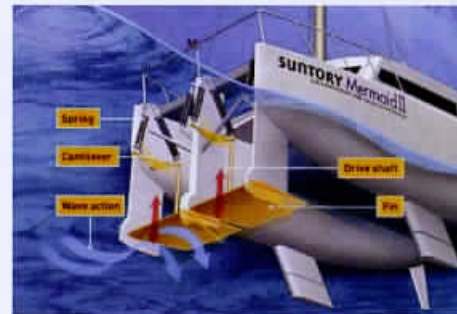


**Abstract:** Conventional overconstrained parallel manipulators have been widely studied both in industry and academia, however the structural synthesis of hybrid mechanisms with additional constraints is seldom studied, especially for the four degrees of freedom(DOF) hybrid mechanisms. In order to develop a manipulator with additional constraints, a class of important spatial mechanisms with coupling chains(CC)s whose motion type is two rotations and two translations(2R2T) is presented. Based on screw theory, the combination of different types of limbs which are used to construct parallel mechanisms and coupling chains is proposed. The basic types of the general parallel mechanisms and geometric conditions of the kinematic chains are given using constraint synthesis method. Moreover, the 2R2T motion pattern hybrid mechanisms which are derived by adding coupling chains between different serial kinematic chains(SKCs) of the corresponding parallel mechanisms are presented. According to the constraint analysis of the mechanisms, the movement relationship of the moving platform and the kinematic chains is derived by disassembling the coupling chains. At last, fourteen novel hybrid mechanisms with two or three serial kinematic chains are presented. The proposed novel hybrid mechanisms and construction method enrich the family of the spatial mechanisms and provide an instruction to design more complex hybrid mechanisms.

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- 710 **Dynamic Analysis of Propulsion Mechanism Directly Driven by Wave Energy for Marine Mobile Buoy.** YU Zhenjiang, ZHENG Zhongqiang, YANG Xiaoguang, and CHANG Zongyu

**Abstract:** Marine mobile buoy(MMB) have many potential applications in the maritime industry and ocean science. Great progress has been made, however the technology in this area is far from maturity in theory and faced with many difficulties in application. A dynamic model of the propulsion mechanism is very necessary for optimizing the parameters of the MMB, especially with consideration of hydrodynamic force. The principle of wave-driven propulsion mechanism is briefly introduced. To set a theory foundation for study on the MMB, a dynamic model of the propulsion mechanism of the MMB is obtained. The responses of the motion of the platform and the hydrofoil are obtained by using a numerical integration method to solve the ordinary differential equations. A simplified form of the motion equations is reached by omitting terms with high order small values. The relationship among the heave motion of the buoy, stiffness of the elastic components, and the forward speed can be obtained by using these simplified equations. The dynamic analysis show the following: The angle of displacement of foil is fairly small with the biggest value around 0.3 rad; The speed of mobile buoy and the angle of hydrofoil increased gradually with the increase of heave motion of buoy; The relationship among heave motion, stiffness and attack angle is that heave motion leads to the angle change of foil whereas the item of speed or push function is determined by vertical velocity and angle, therefore, the heave motion and stiffness can affect the motion of buoy significantly if the size of hydrofoil is kept constant. The proposed model is provided to optimize the parameters of the MMB and a foundation is laid for improving the performance of the MMB.



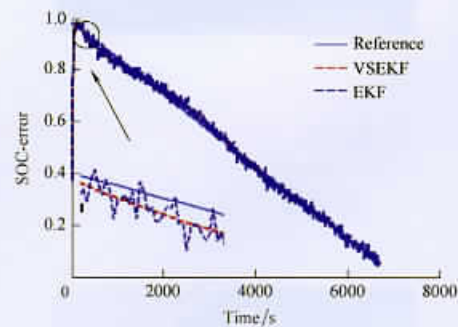
## 716 Selected Paper on Mechanism and Robotics

### Vehicle Engineering

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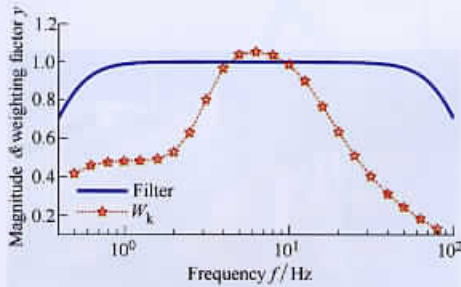
- 717 **Estimation Method of State-of-Charge For Lithium-ion Battery Used in Hybrid Electric Vehicles Based on Variable Structure Extended Kalman Filter.** SUN Yong, MA Zilin, TANG Gongyou, CHEN Zheng, and ZHANG Nong

**Abstract:** Since the main power source of hybrid electric vehicle(HEV) is supplied by the power battery, the predicted performance of power battery, especially the state-of-charge(SOC) estimation has attracted great attention in the area of HEV. However, the value of SOC estimation could not be greatly precise so that the running performance of HEV is greatly affected. A variable structure extended kalman filter(VSEKF)-based estimation method, which could be used to analyze the SOC of lithium-ion battery in the fixed driving condition, is presented. First, the general lower-order battery equivalent circuit model(GLM), which includes column accumulation model, open circuit voltage model and the SOC output model, is established, and the off-line and online model parameters are calculated with hybrid pulse power characteristics(HPPC) test data. Next, a VSEKF estimation method of SOC, which integrates the ampere-hour(Ah) integration method and the extended Kalman filter(EKF) method, is executed with different adaptive weighting coefficients, which are determined according to the different values of open-circuit voltage obtained in the corresponding charging or discharging processes. According to the experimental analysis, the faster convergence speed and more accurate simulating results could be obtained using the VSEKF method in the running performance of HEV. The error rate of SOC estimation with the VSEKF method is focused in the range of 5% to 10% comparing with the range of 20% to 30% using the EKF method and the Ah integration method. In Summary, the accuracy of the SOC estimation in the lithium-ion battery cell and the pack of lithium-ion battery system, which is obtained utilizing the VSEKF method has been significantly improved comparing with the Ah integration method and the EKF method. The VSEKF method utilizing in the SOC estimation in the lithium-ion pack of HEV can be widely used in practical driving conditions.



727 **Frequency Weighting Filter Design for Automotive Ride Comfort Evaluation.** DU Feng

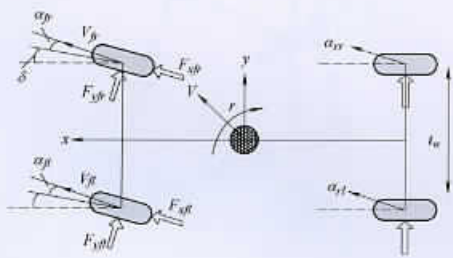
DOI: 10.3901/CJME.2016.0321.034



**Abstract:** Few study gives guidance to design weighting filters according to the frequency weighting factors, and the additional evaluation method of automotive ride comfort is not made good use of in some countries. Based on the regularities of the weighting factors, a method is proposed and the vertical and horizontal weighting filters are developed. The whole frequency range is divided several times into two parts with respective regularity. For each division, a parallel filter constituted by a low- and a high-pass filter with the same cutoff frequency and the quality factor is utilized to achieve section factors. The cascading of these parallel filters obtains entire factors. These filters own a high order. But, low order filters are preferred in some applications. The bilinear transformation method and the least P-norm optimal infinite impulse response(IIR) filter design method are employed to develop low order filters to approximate the weightings in the standard. In addition, with the window method, the linear phase finite impulse response(FIR) filter is designed to keep the signal from distorting and to obtain the staircase weighting. For the same case, the traditional method produces  $0.3307 \text{ m} \cdot \text{s}^{-2}$  weighted root mean square(r.m.s.) acceleration and the filtering method gives  $0.3119 \text{ m} \cdot \text{s}^{-2}$  r.m.s. The fourth order filter for approximation of vertical weighting obtains  $0.3139 \text{ m} \cdot \text{s}^{-2}$  r.m.s. Crest factors of the acceleration signal weighted by the weighting filter and the fourth order filter are 3.0027 and 3.0111, respectively. This paper proposes several methods to design frequency weighting filters for automotive ride comfort evaluation, and these developed weighting filters are effective.

739 **Vehicle Active Steering Control Research Based on Two-DOF Robust Internal Model Control.** WU Jian, LIU Yahui, WANG Fengbo, BAO Chunjiang, SUN Qun, and ZHAO Youqun

DOI: 10.3901/CJME.2016.0112.006



**Abstract:** Because of vehicle's external disturbances and model uncertainties, robust control algorithms have obtained popularity in vehicle stability control. The robust control usually gives up performance in order to guarantee the robustness of the control algorithm, therefore an improved robust internal model control(IMC) algorithm blending model tracking and internal model control is put forward for active steering system in order to reach high performance of yaw rate tracking with certain robustness. The proposed algorithm inherits the good model tracking ability of the IMC control and guarantees robustness to model uncertainties. In order to separate the design process of model tracking from the robustness design process, the improved 2 degree of freedom(DOF) robust internal model controller structure is given from the standard Youla parameterization. Simulations of double lane change maneuver and those of crosswind disturbances are conducted for evaluating the robust control algorithm, on the basis of a nonlinear vehicle simulation model with a magic tyre model. Results show that the established 2-DOF robust IMC method has better model tracking ability and a guaranteed level of robustness and robust performance, which can enhance the vehicle stability and handling, regardless of variations of the vehicle model parameters and the external crosswind interferences. Contradiction between performance and robustness of active steering control algorithm is solved and higher control performance with certain robustness to model uncertainties is obtained.

747 **Experimental Investigation of the Effect of the Material Damage Induced in Sheet Metal Forming Process on the Service Performance of 22MnB5 Steel.** ZHUANG Weimin, XIE Dongxuan, and CHEN Yanhong

DOI: 10.3901/CJME.2016.0513.065

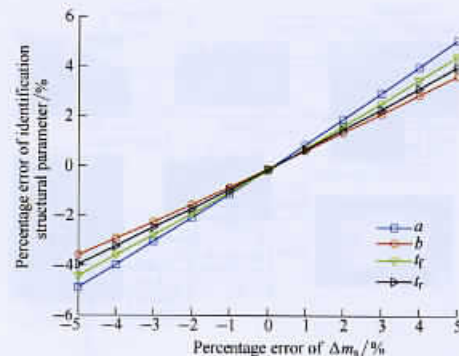


**Abstract:** The use of ultra-high strength steels through sheet metal forming process offers a practical solution to the lightweight design of vehicles. However, sheet metal forming process not only produces desirable changes in material properties but also causes material damage that may adversely influence the service performance of the material formed. Thus, an investigation is conducted to experimentally quantify such influence for a commonly used steel (the 22MnB5 steel) based on the hot and cold forming processes. For each process, a number of samples are used to conduct a uniaxial tensile test to simulate the forming process. After that, some of the samples are trimmed into a standard shape and then uniaxially extended until fracture to simulate the service stage. Finally, a microstructure test is conducted to analyze the microdefects of the remaining samples. Based on the results of the first two tests, the effect of material damage on the service performance of 22MnB5 steel is analyzed. It is found that the material damages of both the hot and cold forming processes cause reductions in the service performance, such as the failure strain, the ultimate stress, the capacity of energy absorption and the ratio of residual strain. The reductions are generally lower and non-linear in the former process but higher and linear in the latter process. Additionally, it is found from the microstructure analysis that the difference in the reductions of the service performance of 22MnB5 by the two forming processes is driven by the difference in the micro damage mechanisms of the two processes. The findings of this research provide a useful reference in terms of the selection of sheet metal forming processes and the determination of forming parameters for 22MnB5.

DOI: 10.3901/CJME.2016.0108.004

756 **Physical Parameter Identification Method Based on Modal Analysis for Two-axis On-road Vehicles: Theory and Simulation.** ZHENG Minyi, ZHANG Bangji, ZHANG Jie, and ZHANG Nong

**Abstract:** Physical parameters are very important for vehicle dynamic modeling and analysis. However, most of physical parameter identification methods are assuming some physical parameters of vehicle are known, and the other unknown parameters can be identified. In order to identify physical parameters of vehicle in the case that all physical parameters are unknown, a methodology based on the State Variable Method(SVM) for physical parameter identification of two-axis on-road vehicle is presented. The modal parameters of the vehicle are identified by the SVM, furthermore, the physical parameters of the vehicle are estimated by least squares method. In numerical simulations, physical parameters of Ford Granada are chosen as parameters of vehicle model, and half-sine bump function is chosen to simulate tire stimulated by impulse excitation. The first numerical simulation shows that the present method can identify all of the physical parameters and the largest absolute value of percentage error of the identified physical parameter is 0.205%; and the effect of the errors of additional mass, structural parameter and measurement noise are discussed in the following simulations, the results shows that when signal contains 30 dB noise, the largest absolute value of percentage error of the identification is 3.78%. These simulations verify that the presented method is effective and accurate for physical parameter identification of two-axis on-road vehicles. The proposed methodology can identify all physical parameters of 7-DOF vehicle model by using free-decay responses of vehicle without need to assume some physical parameters are known.



DOI: 10.3901/CJME.2016.0408.048

765 **Vehicle Detection Based on Visual Saliency and Deep Sparse Convolution Hierarchical Model.** CAI Yingfeng, WANG Hai, CHEN Xiaobo, GAO Li, and CHEN Long

**Abstract:** Traditional vehicle detection algorithms use traverse search based vehicle candidate generation and hand crafted based classifier training for vehicle candidate verification. These types of methods generally have high processing times and low vehicle detection performance. To address this issue, a visual saliency and deep sparse convolution hierarchical model based vehicle detection algorithm is proposed. A visual saliency calculation is firstly used to generate a small vehicle candidate area. The vehicle candidate sub images are then loaded into a sparse deep convolution hierarchical model with an SVM-based classifier to perform the final detection. The experimental results demonstrate that the proposed method is with 94.81% correct rate and 0.78% false detection rate on the existing datasets and the real road pictures captured by our group, which outperforms the existing state-of-the-art algorithms. More importantly, high discriminative multi-scale features are generated by deep sparse convolution network which has broad application prospects in target recognition in the field of intelligent vehicle.



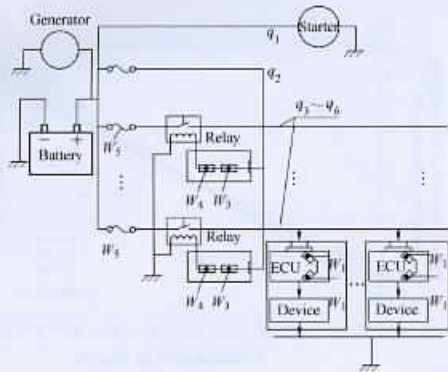
DOI: 10.3901/CJME.2016.0201.018

773 **Damping Collaborative Optimization of Five-suspensions for Driver-seat-cab Coupled System.** ZHAO Leilei, ZHOU Changcheng, and YU Yuewei

**Abstract:** Both the seat and cab system of truck play a vital role in ride comfort. The damping matching methods of the two systems are studied separately at present. However, the driver, seat, and cab system are one inseparable whole. In order to further improve ride comfort, the seat suspension is regarded as the fifth suspension of the cab, a new idea of "Five-suspensions" is proposed. Based on this idea, a 4 degree-of-freedom driver-seat-cab coupled system model is presented. Using the tested cab suspensions excitations as inputs and seat acceleration response as compared output, the simulation model is built. Taking optimal ride comfort as target, a new method of damping collaborative optimization for Five-suspensions is proposed. With a practical example of seat and cab system, the damping parameters are optimized and validated by simulation and bench test. The results show the seat vertical frequency-weighted RMS acceleration values tested for the un-optimized and optimized Five-suspensions are 0.50 m/s<sup>2</sup> and 0.39 m/s<sup>2</sup>, respectively, with a decrease by 22.0%, which proves the model and method proposed are correct and reliable. The idea of "Five-suspensions" and the method proposed provide a reference for achieving global optimal damping matching of seat suspension and cab suspensions.

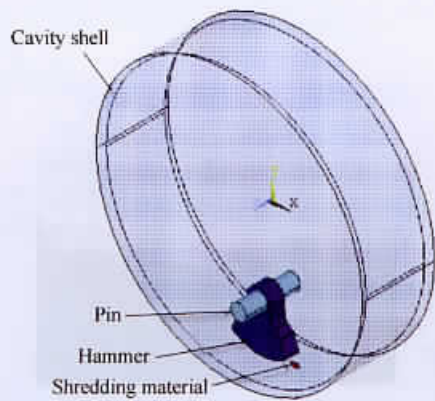


- 781 DOI: 10.3901/CJME.2016.0401.044  
**Intelligent Vehicle Electrical Power Supply System with Central Coordinated Protection.** YANG Diange, KONG Weiwei, LI Bing, and LIAN Xiaomin



**Abstract:** The current research of vehicle electrical power supply system mainly focuses on electric vehicles (EV) and hybrid electric vehicles (HEV). The vehicle electrical power supply system used in traditional fuel vehicles is rather simple and imperfect; electrical/electronic devices (EEDs) applied in vehicles are usually directly connected with the vehicle's battery. With increasing numbers of EEDs being applied in traditional fuel vehicles, vehicle electrical power supply systems should be optimized and improved so that they can work more safely and more effectively. A new vehicle electrical power supply system for traditional fuel vehicles, which accounts for all electrical/electronic devices and complex work conditions, is proposed based on a smart electrical/electronic device (SEED) system. Working as an independent intelligent electrical power supply network, the proposed system is isolated from the electrical control module and communication network, and access to the vehicle system is made through a bus interface. This results in a clean controller power supply with no electromagnetic interference. A new practical battery state of charge (SoC) estimation method is also proposed to achieve more accurate SoC estimation for lead-acid batteries in traditional fuel vehicles so that the intelligent power system can monitor the status of the battery for an over-current state in each power channel. Optimized protection methods are also used to ensure power supply safety. Experiments and tests on a traditional fuel vehicle are performed, and the results reveal that the battery SoC is calculated quickly and sufficiently accurately for battery over-discharge protection. Over-current protection is achieved, and the entire vehicle's power utilization is optimized. The proposed vehicle electrical power supply system is comprehensive and has a unified system architecture, enhancing system reliability and security.

- 792 DOI: 10.3901/CJME.2016.0415.053  
**Failure Mechanisms and Structural Optimization of Shredder Hammer for Metal Scraps.** ZHOU Xianyan, HU Zhili, TAO Yijun, QIN Xunpeng, and HUA Lin



**Abstract:** Recycling retired cars can relieve the environmental pollution and resource waste efficiently. However, a few publications can be found on the failure mechanisms and optimization method of recycling equipment, shredders. Thus, the failure mechanisms and structural optimization of shredder hammers for retired cars are studied aiming improving shredding efficiency and reducing cost. Failure types of shredder hammer are studied theoretically, and it is found that wear failure and fatigue failure are the two main failure types of shredder hammer. The shredding process of metal scraps is analyzed by finite element method, and it can be divided into four stages based on the stress states: initial stage, collision stage, grinding stage and separation stage. It is proved that the shredding efficiency can be improved by increasing cutouts on the hammer head. Finally, it is determined that the hammer with two cutouts is the optimal structure for metal scraps, which can improve the shredding efficiency by 20% and lengthen the hammer life by 15%. This study provides scientific basis for the industry application and theoretical foundation for further research.

802 Selected Paper on Vehicle Engineering

## Fluid and Power Machinery

- 803 DOI: 10.3901/CJME.2016.0414.052  
**Entropy Production Analysis for Hump Characteristics of a Pump Turbine Model.** LI Deyou, GONG Ruzhi, WANG Hongjie, XIANG Gaoming, WEI Xianzhu, and QIN Daqing

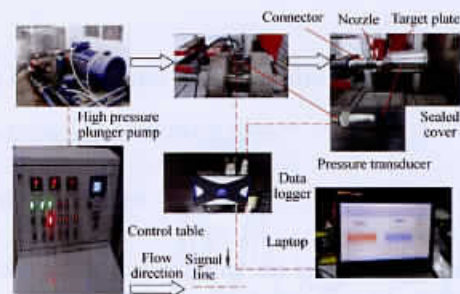


**Abstract:** The hump characteristic is one of the main problems for the stable operation of pump turbines in pump mode. However, traditional methods cannot reflect directly the energy dissipation in the hump region. In this paper, 3D simulations are carried out using the SST  $k-\omega$  turbulence model in pump mode under different guide vane openings. The numerical results agree with the experimental data. The entropy production theory is introduced to determine the flow losses in the whole passage, based on the numerical simulation. The variation of entropy production under different guide vane openings is presented. The results show that entropy production appears to be a wave, with peaks under different guide vane openings, which correspond to wave troughs in the external characteristic curves. Entropy production mainly happens in the runner, guide vanes and stay vanes for a pump turbine in pump mode. Finally, entropy production rate distribution in the runner, guide vanes and stay vanes is analyzed for four points under the 18 mm guide vane opening in the hump region. The analysis indicates that the losses of the runner and guide vanes lead to hump characteristics. In addition, the losses mainly occur in the runner inlet near the band and on the suction surface of the blades. In the guide vanes and stay vanes, the losses come from pressure surface of the guide vanes and the wake effects of the vanes. A new insight-entropy production analysis is carried out in this paper in order to find the causes of hump characteristics in a pump turbine, and it could provide some basic theoretical guidance for the loss analysis of hydraulic machinery.

- 813 **Effects of Area Discontinuity at Nozzle Inlet on the Characteristics of Self-resonating Cavitating Waterjet.** LI Deng, KANG Yong, DING Xiaolong, WANG Xiaochuan, and FANG Zhenlong

DOI: 10.3901/CJME.2016.0426.060

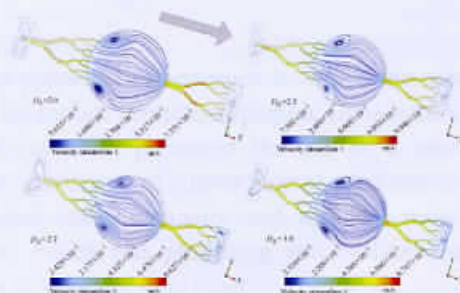
**Abstract:** The current research on self-resonating cavitating waterjet(SRCW) mainly focuses on the generation mechanism and structure optimization. Researches relating to the influences of disturbances at nozzle inlet on the characteristics of the jet are rarely available. In order to further improve the performance of SRCW, effects of area discontinuity(enlargement and contraction) are experimentally investigated using three organ-pipe nozzles. Axial pressure oscillation peak and amplitude as well as aggressive erosion intensity of the jet are used to evaluate the effects. The results reveal that area enlargement and contraction affect the peak differently, depending on the inlet pressure, nozzle geometry, and standoff distance; while area contraction always improves the amplitude regardless of these factors. At inlet pressures of 10 MPa and 20 MPa, area discontinuity improves the peak at almost all the testing standoff distances, while this only happens at smaller standoff distances with the inlet pressure increased to 30 MPa. The capability of area discontinuity for improving the amplitude is enhancing with increasing inlet pressure. Moreover, the cavitation erosion ability of the jet can be largely enhanced around the optimum standoff distance, depending on the type of area discontinuity and nozzle geometry. A preliminary analysis of the influence of area discontinuity on the disturbance waves in the flow is also performed. The proposed research provides a new method for effectively enhancing the performance of SRCW.



- 825 **3D FEM Analyses on Flow Field Characteristics of the Valveless Piezoelectric Pump.** HUANG Jun, ZHANG Jianhui, SHI Weidong, and WANG Yuan

DOI: 10.3901/CJME.2016.0427.061

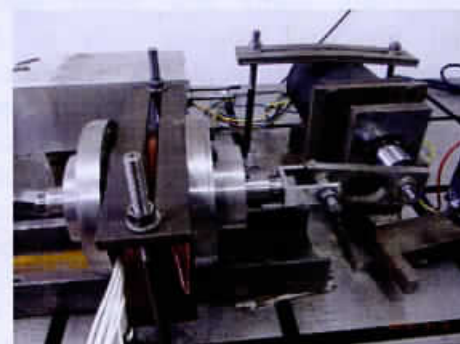
**Abstract:** Due to the special transportation and heat transfer characteristics, the fractal-like Y-shape branching tube is used in valveless piezoelectric pumps as a no-moving-part valve. However, there have been little analyses on the flow resistance of the valveless piezoelectric pump, which is critical to the performance of the valveless piezoelectric pump with fractal-like Y-shape branching tubes. Flow field of the piezoelectric pump is analyzed by the finite element method, and the pattern of the velocity streamlines is revealed, which can well explain the difference of total flow resistances of the piezoelectric pump. Besides, simplified numerical method is employed to calculate the export flow rate of piezoelectric pump, and the flow field of the piezoelectric pump is presented. The FEM computation shows that the maximum flow rate is 16.4 mL/min. Compared with experimental result, the difference between them is just 55.5%, which verifies the FEM method. The reasons of the difference between dividing and merging flow resistance of the valveless piezoelectric pump with fractal-like Y-shape branching tubes are also investigated in this method. The proposed research provides the instruction to design of novel piezoelectric pump and a rapid method to analyse the pump flow rate.



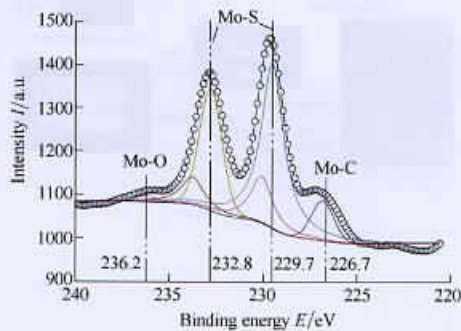
- 832 **Design of a Transverse-flux Permanent-magnet Linear Generator and Controller for Use with a Free-piston Stirling Engine.** ZHENG Jigui, HUANG Yuping, WU Hongxing, and ZHENG Ping

DOI: 10.3901/CJME.2016.0429.063

**Abstract:** Transverse-flux with high efficiency has been applied in Stirling engine and permanent magnet synchronous linear generator system, however it is restricted for large application because of low and complex process. A novel type of cylindrical, non-overlapping, transverse-flux, and permanent-magnet linear motor(TFPLM) is investigated, furthermore, a high power factor and less process complexity structure research is developed. The impact of magnetic leakage factor on power factor is discussed, by using the Finite Element Analysis(FEA) model of stirling engine and TFPLM, an optimization method for electro-magnetic design of TFPLM is proposed based on magnetic leakage factor. The relation between power factor and structure parameter is investigated, and a structure parameter optimization method is proposed taking power factor maximum as a goal. At last, the test bench is founded, starting experimental and generating experimental are performed, and a good agreement of simulation and experimental is achieved. The power factor is improved and the process complexity is decreased. This research provides the instruction to design high-power factor permanent-magnet linear generator.



## Friction and Wear



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### Investigation on MoS<sub>2</sub> and Graphite Coatings and Their Effects on the Tribological Properties of the Radial Spherical Plain Bearings. QIU Ming, LU Jianjun, LI Yingchun, and LV Guisen

**Abstract:** With constant enlargement of the application areas of the spherical plain bearings, higher quality lubrication of the bearings is required. To solve the lubricating problems of spherical plain bearings under high temperature, high vacuum, high speed, heavy loads and strong oxidation conditions, it is urgent for us to develop more excellent self-lubricating technologies. In this paper, the bonded solid lubricant coatings, which use inorganic phosphate as the binder, the mixture of MoS<sub>2</sub> and graphite with two different weight proportions as the solid lubricant, are prepared by spraying under three different spray gun pressures. The bonding strength tests on the coatings show that the best spraying pressure is 0.2 MPa and the better mixing proportion of MoS<sub>2</sub> to Graphite is 3:1. Then for the radial spherical plain bearings with steel/steel friction pair, after the coatings are made on the inner ring outer surfaces, the friction coefficient, the wear loss and the friction temperature of the bearings under four oscillating frequencies are investigated by a self-made tribo-tester. The test results, SEM of the worn morphologies and EDS of worn areas show that tribological properties of the bearing are obviously improved by the bonded solid lubricant coatings. When sprayed under the spray gun pressure of 0.2 MPa, the bearings have better anti-friction and anti-wear properties than those sprayed under 0.1 MPa and 0.3 MPa. Further as proved from the XPS analysis, between the coating with 3:1 mixing ratio of MoS<sub>2</sub> to Graphite and the coating with 1:1 ratio, the former has less oxidation occurred on the surface and therefore has better tribological characteristics than the latter. This paper provides a reference to developing a new product of the radial spherical plain bearings with high bonding strength, oxidation resistance and abrasion resistance.

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### Synthesized Multi-station Tribo-test System for Bio-tribological Evaluation in Vitro. WU Tonghai, DU Ying, LI Yang, WANG Shuo, and ZHANG Zhinan

**Abstract:** Tribological tests play an important role on the evaluation of long-term bio-tribological performances of prosthetic materials for commercial fabrication. Those tests focus on the motion simulation of a real joint in vitro with only normal loads and constant velocities, which are far from the real friction behavior of human joints characterized with variable loads and multiple directions. In order to accurately obtain the bio-tribological performances of artificial joint materials, a tribological tester with a miniature four-station tribological system is proposed with four distinctive features. Firstly, comparability and repeatability of a test are ensured by four equal stations of the tester. Secondly, cross-linked scratch between tribo-pairs of human joints can be simulated by using a gear-rack meshing mechanism to produce composite motions. With this mechanism, the friction tracks can be designed by varying reciprocating and rotating speeds. Thirdly, variable loading system is realized by using a ball-screw mechanism driven by a stepper motor, by which loads under different gaits during walking are simulated. Fourthly, dynamic friction force and normal load can be measured simultaneously. The verifications of the performances of the developed tester show that the variable frictional tracks can produce different wear debris compared with one-directional tracks, and the accuracy of loading and friction force is within 5%. Thus the high consistency among different stations can be obtained. Practically, the proposed tester system could provide more comprehensive and accurate bio-tribological evaluations for prosthetic materials.



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