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Intelligent diagnosis of bearing knock faults in internal combustion engines using vibration simulation

Jian Chen [a,b,*], Robert Bond Randall [b]

[a] Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, UK
[b] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney 2052, Australia

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ABSTRACT

Big-end bearing knock faults in IC engines can be considered as a real industrial case of a slider-crank mechanism including a joint with clearance and lubrication. In this paper, an Artificial Neural Network (ANN) based system was used to solve the problem of intelligent big-end bearing knock fault diagnosis in Internal Combustion (IC) engine. But when the ANN is used in machine condition monitoring, it is either unlikely or uneconomical to experience all different real faults to generate sufficient training data. Therefore, model based method should be a viable way to generate adequate data to train the networks for the intelligent big-end bearing fault diagnosis in IC engines. In order to evaluate and update the simulation model, experiments with normal bearing clearance and with different oversize bearing clearances were first carried out on the engine test rig. It was found that the relevant diagnostic information lies in the squared envelope of the vibration signals. Therefore, we only need build a proper simulation model to simulate the correct envelope signals rather than the raw vibration signals. As the important inputs of the simulation model, the inertia properties of the simulated engine components were also measured and studied. Next, we built an ANN-based bearing knock diagnosis system which consists of three phases: fault detection phase, fault localization phase and fault severity identification phase. Particularly, a saturating linear function is selected as the transfer function of the fault severity identification stage, so the networks can linearly classify the fault levels and the output is more in agreement with the reality in industry. Following the feature extraction and selection from the processed squared envelope signals, the networks were purely trained by the simulated data with normal bearing clearance and with different oversize bearing clearances. Finally the networks was tested by the real experimental data and it was demonstrated that the networks can successfully detect different bearing knock faults in real tests, and also classify the faults' location and severity levels.

1. Introduction

IC engines have severe operating conditions, involving high temperatures and high pressures, with large variations in internal forces within each cycle, and as such the wear mechanisms are complex. The journal bearings of IC engines are particularly vulnerable to these conditions, as opposed to those in rotating machines such as turbogenerators, because of the extreme variations in load. Therefore bearing damage, especially the big-end bearing damage, due to friction and wear accounts for and leads to a

* Corresponding author at: Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, UK.
E-mail addresses: jc2d14@soton.ac.uk, jian.chen1@unsw.edu.au (J. Chen).

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significant portion of Internal Combustion (IC) engine failure [1]. However, only few works have addressed the issue of big end bearing knock fault diagnosis based on vibration measurement. Moreover, traditional vibration based diagnostic techniques normally require engineers to analyse the vibration signal by means of their experience. Recently, Artificial Neural Networks (ANNs) based automated system has been successfully developed and applied to the diagnosis of rotating machinery. Therefore, following the proper signal processing method and feature extraction/selection method, ANN should also be a potential solution to realize the intelligent diagnosis of the big end bearing faults in IC engines. The successful application of ANN is strongly depended on the adequate data for the networks' training. Both data-driving approach and model-based approach are the solutions to this issue. The former approach requires very long-term data record from one IC engine or a large number of identical engines, so it is a very expensive approach. Alternatively if a relevant simulation model is built up, different bearing knock faults can be easily simulated in the model, so sufficient training data can be generated as well. Beforehand only a small number of experiments need to be carried out on the engine test rig so as to evaluate the simulation model.

Big-end bearing knock faults in IC engines are a typical issue of a slider-crank mechanism with an oversize clearance joint and lubrication. Many researchers have addressed the dynamic modelling of the dry or lubricated evolute joints (journal bearing) with clearance in the slider-crank mechanism [2–6]. Even though all of the works are focussed on the modelling of the small end bearing with clearance, the analysis methods can also be extended to the modelling of the big end bearing with clearance in IC engines. Particularly, Daniel and Cavalca [6] analytically developed the kinematic model and hydrodynamic model for the evolute joint between piston and connecting rod with clearance and lubrication, and they used a numerical technique to iteratively compute the kinematic/kinetic equations and the lubrication equations, and finally solved the multi-Degree-Of-Freedom (DOF) problem raised by the non-negligible clearance.

This paper can be considered as the extension and a real application of modelling methods developed by Refs. [5,6] and also our former work [7]. The critical issue for the model based intelligent condition monitoring is the model should create the signals with decent accurate diagnostic information, so normally a small number of experiments should be carried out on the engine test rig first. In this paper, after the advanced signal processing techniques were applied to process the experimental vibration signals, we found that the most useful diagnostic information lies in the squared envelopes of vibration signals. Therefore, even though many more sophisticated analytical modelling methods or finite element modelling methods have been developed for the journal bearing design in recent years, for the intelligent big-end bearing fault diagnosis, we only need to apply a proper modelling approach to generate accurate envelope signals rather than raw accelerations (or impact forces). The simulation model for the bearing knock diagnosis consists of the kinematic/kinetic part and the hydrodynamic part. The lubrication forces (bearing knock force) which is the interconnection between two models was numerically solved step by step. Based on the measured transfer functions between the bearing houses to the measurement point on the engine block, vibration signals were further calculated from the simulated bearing knock forces. As the important inputs of the simulation model, the parameters of the relevant engine components, such as the inertial properties, were also measured and calculated by some measurement techniques. Based on the experimental data, the amplitude and phase features of the Fourier coefficients of the squared envelopes were extracted. Particularly, the Genetic Algorithm (GA) was used select the best amplitude features as the inputs of the networks. Next, we used purely simulated data to train the three-phase network system, which consists of two MLP (Multi Layer Perceptron) networks for fault detection (MLP1) and fault severity identification (MLP2), and one PNN (Probabilistic Neural Network) for the fault localization. The selected amplitude features were used as the inputs of the MLP1 and MLP2, and the selected phase features were used as the inputs of the PNN. Finally the real experimental data were inputted into the intelligent diagnosis system to test its performance and it was demonstrated that the intelligent system got good results.

2. Principle of bearing knock

2.1. Kinematic/kinetic principle

If all the joints of piston-connection rod-crank system are perfect joints, the dynamics of the system is a classic signal-DOF issue. But if an oversize clearance is introduced into the big end bearing joint, the dynamic properties become more complicated and there are two pendulum motions in this mechanism system, one is the rocking motion of the connecting rod about the piston pin and the other is relative to the almost constant rotational speed of the crank pin. So the piston-connection rod-crank system become a multi-DOF system (as shown in Fig. 1), and it can be separated into two subsystems, piston and connecting rod subsystem and crank subsystem. It is not difficult to build separate kinematic/kinetic equations for the two subsystems, but in order to solve this multi-DOF issue, the hydrodynamic lubrication equations which can introduce extra “constraints” into the system should be added into the system. Note that we only considered the oversize clearance in the big end bearing joint in this paper, so we assumed both the piston pin (small end bearing) joint and crank main journal (joint) are perfect joints.

As shown in Fig. 1, the whole system has three external forces/moments, F_d is the combustion force, T_f represents both friction torque and pumping torque of the engine, T_l represents the engine external load. We always consider the combustion pressure is evenly distributed on the top of the piston in this paper, so the combustion force F_d can be just integrated from the pressure about the piston top area. We will use subscript c and subscript j to represent the parameters associated with connecting rod (big end bearing) and crank journal in the following sections. For the connecting rod with a total length of c_c, we can measure the location of its centre of gravity (CG) and the detail of inertial property measurement of the connecting rod will be presented in Section 3.3. The distances from the centre of the small end to the centre of gravity (CG) of the connecting rod are