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A control method of the rotor re-levitation for different orbit responses during touchdowns in active magnetic bearings

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ABSTRACT

Touchdown can make active magnetic bearings (AMB) unable to work, and bring severe damages to touchdown bearings (TDB). To resolve it, we presents a novel re-levitation method consisting of two operations, i.e., orbit response recognition and rotor re-levitation. In the operation of orbit response recognition, the three orbit responses (pendulum vibration, combined rub and bouncing, and full rub) can be identified by the expectation of radial displacement of rotor and expectation of instantaneous frequency (IF) of rotor motion in the sampling period. In the rotor re-levitation operation, a decentralized PID control algorithm is employed for pendulum vibration and combined rub and bouncing, and the decentralized PID control algorithm and another whirl damping algorithm, in which the weighting factor is determined by the whirl frequency, are jointly executed for the full rub. The method has been demonstrated by the simulation results of an AMB model. The results reveal that the method is effective in actively suppressing the whirl motion and promptly re-levitating the rotor. As the PID control algorithm and the simple operations of signal processing are employed, the algorithm has a low computation intensity, which makes it more easily realized in practical applications.

1. Introduction

Touchdown bearing (TDB) is an essential part in active magnetic bearings (AMB) to prevent the excessive displacements during the rotor-TDB interaction due to the AMB components or power failure to protect the AMB laminations from permanent damages [1]. The dynamic behavior of the rotor is very complicated due to the rotor-TDB interaction [2–4]. According to ISO 14839 [5], the rotor may exhibit three states of the orbit responses, including: pendulum vibration, combined rub and bouncing, and full rub in touchdowns. Full rub is a rare but potential threat to the AMB system due to the large rotor-TDB contact forces and the whirl frequency and the motion has been widely analyzed both in theoretical and experimental researches [6–10]. During the onset phase of full rub, the whirl frequency may increase continuously until it locks to the eigenfrequencies of the rotor-TDB system [2,11–13]. For safety considerations of AMB equipment, protective measures should be taken during full rub.

Many appropriate design considerations of TDBs has been recommended in Ref. [1], such as low friction between the rotor and TDB, an elastically soft support with damping to limit the whirl frequency and the contact force as well as adding special components to damp the rotor-TDB impacts, etc. Jin et al. [14,15] proposed the double-decker touchdown bearing and analyzed the thermal structure of it. The new type of touchdown bearing can significantly reduce the temperature rise

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compared with single-decker touchdown bearing. Yu and Jin [16] proposed the auto-eliminating clearance touchdown bearing devices which can automatically eliminate the protective clearance between the outer race of TDB and the support during touchdowns. The device could effectively reduce the impact forces and eliminate the possibility of incurring full rub. Corrugated ribbon which creates a circumferential damping has been proposed by Schmied and Pradetto [17]. They also suggested that a sufficient low moment of inertia of the inner race and a low friction coefficient between the rotor and the inner race were expected. Wilkes et al. [18] also utilized the ribbon damper between the catcher bearing and housing to provide compliance and damping to the ball bearing. These methods are considered as passive protective measures to reduce the possibility of full rub and to decrease the vibration frequency and the contact forces in touchdowns.

In addition, some researches attempted to employ active protective measures by AMBs to restrain the touchdown vibration and re-levitate the rotor during touchdowns caused by transient AMB failures. Caprio et al. [19] performed touchdown tests and a semi-passive whirl arresting scheme for a 130 kW-hr power averaging flywheel battery to be used on high speed passenger trains. They devised and tested a semi-passive whirl arresting scheme to allow the operators to manually stop the whirl motion in case of the failure of magnetic bearings. An additional switched passive whirl arresting circuit was installed in the AMB system. When the AMB was switched into whirl arresting mode by the operator, a 'gravity' field was imposed on the rotor by a bias current with the AMB. The rotor was pulled into one particular radial quadrant and subsequently arrested by AMBs. However, the method could not automatically monitor the touchdown events, distinguish the orbit responses and promptly switch the control algorithm to reduce the rotor vibration and re-levitate the rotor during whirl motion.

Keogh and Cole [20–22] found that significant phase changes appeared during touchdowns and proposed new approaches which were derived by H-infinity and steady state norm-bound design criteria for control strategy. The new approaches were proved to be successful in the experiments to recover the rotor from touchdown conditions. The patent EP 2006556A1 [23] demonstrated another rotor re-levitation method during touchdowns in magnetic molecular pumps. The invented device was specially adapted to control the rotor position in a touchdown situation and it was comprised of the first control modules (the contact-less manner) and the second control modules (the touchdown manner). The output signals of the first and second control modules were added by a weighting factor which was in dependence on changes in rotor dynamics. The second control module provided resilience forces on the rotor to damp the whirl motion. Recovery after a touchdown in the touchdown bearings during rotation was improved. However, the device was triggered just when rotor touches one of touchdown bearings and it lacked of the orbit recognition procedure between the three responses defined in ISO 14839 [5]. The method relied strongly on the particular pump type. The control algorithm may not achieve the rotor re-levitation operation when used in other AMB systems or the touchdown condition was not previously written in the database.

The recognition of the orbit responses contributes to the selection of the most suitable control algorithm in the AMB controller. The three orbit responses can be identified by the rotor orbits based on the engineering experience. ISO 14839 [5] illustrates that by comparing the dynamic forces and the static loads during touchdowns, pendulum vibration and combined rub and bouncing can be identified. However, the dynamic forces on the rotor are difficult to measure precisely for the force transducers are seldom installed in the AMB equipment. Lyu et al. [24] have analyzed the time-frequency characteristics of these orbit responses during touchdowns and pointed out that the instantaneous frequency (IF) calculated by Hilbert transform showed significant differences between these responses and IF could be used to identify them. IF is able to trace the frequency variation of the orbit responses along with time thus it can better reveal the instantaneous change of the frequency and amplitude compared with wavelet transform [25].

In comparison with full rub, the orbit responses of pendulum vibration and combined rub and bouncing have lower rotor-TDB contact forces, so the rotor re-levitation operation is easier and can be achieved by the suspension control algorithm. The established full rub, however, has the largest rotor-TDB contact forces which may higher than the maximum electromagnetic forces provided by AMB and the rotor re-levitation operation only by the suspension control algorithm is difficult. A control algorithm which can decrease the frequency and amplitude of whirl motion is required to reduce the AMB damage and promptly re-levitate the rotor. This paper presents a novel rotor re-levitation method which is able to monitor the suspension status of the AMB rotor in real-time, recognize the orbit responses during touchdowns and switch the control algorithms in different orbit responses. The rotor re-levitation method, including the orbit response recognition and the rotor re-levitation operation, has been elaborated in Section 2. To demonstrate the rotor re-levitation method, a simulation model, including a thermo-dynamic model of the rotor-TDB system and an AMB control system model have been established in Section 3. The simulated results of touchdown process and re-levitation process are shown in Section 4 and main conclusions are shown in Section 5.

2. Rotor re-levitation method during touchdowns

The rotor re-levitation method consists of two procedures, orbit response recognition and rotor re-levitation operation, as shown in Fig. 1. Since the dynamic characteristics of these orbit responses is considerably different, the control algorithms in the re-levitation operation are different.

2.1. Orbit response recognition

Three typical orbit responses can be found during touchdowns of AMB rotors, including pendulum vibration, combined rub and bouncing and full rub, according to ISO-14839 [5]. In combined rub and bouncing, the average radial displacement of