論 文 の 内 容 の 要 旨

論文題目　A compact magnetically levitated transverse flux permanent magnet linear synchronous motor
--- Surrogate assisted rapid design and suspension control ---

(磁気浮上で支持される小型横磁束形リニア同期モータの研究 ---サロゲートモデルに基づく高速設計と能動浮上制御---)

氏　　名　　アーメド　サルマン

Linear motors with contactless suspension has always fascinated engineers and researchers owing to their awe inspiring characteristics of zero friction, no wear and tear, high positioning accuracy, and high speeds. In literature, many different kinds of linear motors can be found, with two main categories based on field excitation, which are linear induction (LIM) and linear synchronous motors (LSM). Similarly, contactless suspension can also be achieved with different technologies such as air bearings, electrodynamic (EDS) and electromagnetic (EMS) suspension. Combining both propulsion and suspension, results in one of the most well known application of contactless suspended linear motor driven stage, the electric railways. However, due to the inherent advantage of being able to achieve ultra high positioning accuracy, magnetically levitated transport carrier systems also have the potential to be used in fields such as precision machinery including semiconductor fabrication and optical component manufacturing, high speed machining, factory conveyance including pick and place *etc*.

With a thorough review of the current state of contactless stages aimed at industrial applications, especially in manufacturing, one can find a diverse set of stages with various propulsion and suspension technologies combined. Among them, use of permanent magnets (PM) for suspension and traction is a common sight. Although, LIMs provide a simple structure with easy integration with EMS, the thrust density compared with iron-cored PMLSMs is fairly less. On the other hand, repulsive type PM based EDS combined with ironless PMLSMs is often deployed for short stroke ultra precision stages, but it also suffers from low thrust density and loading capacity. In light of the above argument, a compact contactless stage with high thrust density iron-cored PMLSMs is still not widely used. This is attributed to the strong attraction of

PMs to the armature cores in longitudinal (detent) and normal (normal stiffness) directions which hinders high precision positioning as well as reduces the effective loading capacity. In response to it, a comprehensive study on possible combination of iron-cored PMLSM with EMS is conducted in this research, while providing viable solutions to the inherent problems of large thrust ripple and normal stiffness.

Various topologies of iron-cored PMLSMs exist in literature, however, based on its high thrust density and ease of manufacturing, a unique transverse flux type PMLSM is considered as a propulsion actuator. With it in mind, a novel magnetically suspended variant is proposed, which is a double sided TF-PMLSM (about vertical and lateral axes) with E-shaped electromagnets as armature's back iron responsible for providing active suspension in three degrees of freedom (DOF) namely, heave, roll and pitch. The remaining two DOF, guidance and yawing, are passively stabilized due to the symmetrical structure about vertical axis. With slight lateral deviation, a restoring force

acts to force the armature (mover) to the center. This feature is characterized by lateral stiffness. In addition, the normal stiffness, which is a consequence of PMs attraction to iron core, is relatively small due to the double sided structure about the lateral axis. Furthermore, it is shown by sensitivity analysis that, despite being completely contactless, the influence of positional deviation along transverse plane is negligible to the linear motion (Electromagnetic thrust). Likewise, influence of linear displacement to the normal and lateral stiffnesses is negligible, resulting in relaxed disturbance rejection performance for suspension controller. Following the proposal of the machine, this research is mainly divided into two parts: 1) The optimal design of the linear motor in consideration of suspension characteristics and detent force reduction. 2) Suspension control.

Unlike conventional linear motors, transverse flux machines having magnetic flux paths orthogonal to the motion direction absolutely require the three dimensional (3D) finite element method (FEM) to evaluate its performance characteristics such as thrust, detent force, no load back emf *etc*. This makes the design of transverse flux machines, and generally machines with complex three dimensional magnetic flux path, computationally expensive. With increasing design parameters and multi-objectives, present available design of experiment (DOE) and response surface/surrogate based methods (RSM) are unable to achieve optimal design in a timely manner. Therefore, we propose to use the multi-fidelity surrogate assisted method to accelerate the design flow. Multi-fidelity methods combine information from two different models, each of varying fidelity such as a high fidelity (HF) one with high accuracy and a high computational cost, and a low-fidelity (LF) model with low accuracy and low cost. By constructing a LF-model of transverse flux machine using equivalent magnetic reluctance, simulation time is reduced at the cost of accuracy. However, smartly integrating the HF data to rectify the LF surrogate, a multi-fidelity response surface is constructed in a fraction of time compared to conventional DOE methods. The said method is applied to the proposed TF-PMLSM as a case study with seven design parameters and three objectives, thrust, normal and lateral stiffnesses.

Unlike thrust, detent force has a higher order dependency on motor dimensions, and thus would require dense sample plans for its surrogate construction, which is practically an impediment to rapid design. To treat this problem, a unique approach to peak detent force calculation with minimal number of high fidelity simulations is proposed, hereby reducing the computational burden. We employ the multi-fidelity variant of Gaussian process regression (kriging), called co-kriging to estimate the detent waveform using HF and LF models, and then treat the detent waveform itself as an maximization and minimization problem to search for peak values using expected improvement (EI) strategy. This leads to peak values of detent waveform in a mere fraction of time, compared to existing exhaustive methods. In addition, we also delve upon detent reduction methods based on destructive interference of each core's contribution. A sectioning method is proposed which can further minimizes the dominant enf-effect detent force. As a result, an extremely low detent machine is obtained with a thrust to detent ratio of 196/0.45.

With the machine manufactured as per results obtained from part one, part two deals with the analysis and control of the suspension of the motor. Design and analysis of the electromagnets is conducted in consideration to the attractive influence of PMs of linear motor. Being a double sided structure, although ideally the attractive force of PMs are canceled out, but slight eccentricity results in a net normal force. For iron-core PMLSMs, it can be significant and if not considered in the suspension modeling, can be fatal to operation. We propose to model the distributed influence of PM on armature core over the length of the motor and transform them to suspension coordinates leading to a relatively better dynamic model. It is shown that in doing so, the minimal bandwidth requirement for stable suspension can be calculated. Furthermore, control design based on the improved model reduces somewhat the requirement for a conservative controller.

With an effectively accurate dynamic model, suspension controllers are designed, starting with a conventional IPD one, to demonstrate the feasibility of the concept. In addition, due to the large non-linearity as well as coupling between DOF, a reference model based non-linearity inversion compensation is applied to extend the operating range. Lastly, an outlook towards future is given based on author's personal experience obtained during the coarse of this project on design of such magnetically levitated motors.