

論文の内容の要旨

論文題目 Response Based Track Profile Estimation Using Observable
Train Models with Numerical and Experimental
Validations
(可観測な車両モデルを利用した応答計測型軌道変位
推定とその検証)

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Railway technology has developed in line with Japanese social and economic changes and has seen rising speeds, cost saving and safety, as well as falling environmental impact. However, local railway networks suffer from age-related deterioration and poor maintenance and also it might be unable to perform adequate monitoring. It is essential to improve the comfort level and service life of local railway lines. Track profile which directly influences the ride quality and safety of rail tracks need to be estimated for the maintenance purpose. Currently, Track Recording Vehicle (TRV) like Doctor Yellow, one high speed test train in Japan is utilized for the track condition monitoring. But the demerits of TRV are, that it is expensive and cannot be frequently used for local railway lines. It is used only once in a year for most of lines. So, track profile estimation through vehicle response measurements potentially provides efficient and frequent measurement. However, the current onboard measurement system still stays on the qualitative inspection by repetitive tests. The main challenge to detect the vertical and lateral track profile and the other rail track irregularities is the unstable solution for the inverse analysis. A simpler, more robust and cost effective system for in-service train vehicle is desirable. Thus, data assimilation method is necessary for estimating the unknown inputs. For inverse analysis

technique generally augmented Kalman Filter is being utilized. However, issue of un-observability need to be solved.

From the above background study, the research objectives of this dissertation are as follows,

- To propose extended Augmented State Kalman Filter (ASKF) technique to solve the Observability Rank Condition (ORC) for the state space model.
- To estimate both vertical and lateral railway track profile using extension of ASKF data assimilation technique for a rigid body motion train model.
- To perform Multi-Body Simulations (MBS) using SIMPACK to investigate the influence from different factors under various scenarios and to validate the proposed estimation algorithm.
- To validate the proposed inverse analysis on experimental measurements obtained from in-service local railway line.

Firstly, while the measurement of track profile or vehicle's absolute displacement on board is not practical, but the acceleration and angular velocity measurements are feasible. Prevalent sensing devices such as smartphones have been potentially being utilized in vehicle body motion measurement. However, the applicability of inverse analysis for track profile estimation from such measurement is not clarified yet. Hence, from the perspective of observability, sensor installation location's effect needs to be investigated. Observability is the method or a concept to explain whether the particular state of the dynamic system can be identified under a given subset of limited measurements. In this study, ORC analysis of various time invariant linear vehicle dynamic models with different measurement layout are carried out to obtain the appropriate sensor placement strategy. The analysis shows that the profile becomes unobservable under acceleration and angular velocity measurements. To overcome this issue, in this dissertation the second derivative of the profile is proposed to be augmented in the state vector as one of the additional state variable, and thus the track profile component can be obtained through double integration of it. The proposed approaches theoretically solved the issue of un-observability and also revealed a sensor type and placement strategy, which can be used as the guideline in the track profile estimation through train vehicle response measurement.

Secondly, for numerical analysis purpose, vehicle body acceleration (vertical and lateral) and angular velocity measurements (pitching and yawing) are considered. In this dissertation, Kalman filter technique is employed for state space models termed as conventional ASKF and two extended approaches for the track profile estimation by augmenting the second derivative of profile directly or adopting the first derivative of the original state vector. The recommended estimation algorithm ASKF is robust and fast, which competently process the data collected

from sensors through a simple linear rigid body train vehicle model. The verification study for simplified train models (4 DOF) and 6 DOF train models, accounting for both vertical and lateral track profile estimation are carried out and results are found to be in good agreement. In order to obtain the quantitative comparison of two waveforms, phase-shift correction is carried out using the misfit criteria through Hilbert transform. The statistical metrics are utilized for obtaining the single-valued misfit between two waveforms. Therefore, depending upon the sensors availability and feasible sensor placement locations, track profile can be reconstructed using extended ASKF algorithm with proposed method.

Thirdly, to perform MBS using SIMPACK: Rail, to generate more realistic responses by considering the influence from different factors under various scenarios, namely straight track and splined track sections. The sensors are placed just above the rail tracks on both the sides and used to measure the acceleration and angular velocity responses from the car body and both bogie masses of running train model on simulated track sections with vertical and lateral excitations. These vehicle measurement responses are utilized to estimate the vertical and lateral track profile using the 4 DOF simplified model as well as 6 DOF train model and it is validated using the proposed estimation algorithm. The suggested sensor placement strategy is compared with maximum sensor location case and found to perform well. For straight track section (ideal case), it shows a good agreement for vertical track profile while it can estimate only above 8 m wavelength irregularity for lateral track profile. The statistical metrics are utilized for comparison between various cases and the proposed approach is verified. Also, MBS are carried out for understanding the influence of rolling motion of train vehicle. For curved track section, the results show good agreement for vertical track profile estimation, while it shows large variation for lateral profile estimation. This is due to hunting oscillation phenomenon. Exactly the splined section of the track cannot be evaluated, because of wheel-rail interaction problem.

Lastly, to perform the rail track profile estimation from the in-service vehicle response measurement proposed extended ASKF method is employed. The smartphones (low cost sensors) are mounted on the train car body floor to collect the train vehicle dynamic responses. Inverse analysis is carried out to estimate both the vertical and lateral track irregularity by reconstructing the track profile waveform as well as converted 10 m chord versine waveform. The results are found with slight deviations due to simplified 4 DOF model and other phenomenon like hunting oscillation motion. This is due to practical limitations of sensor placement only on the car body. In future experimental measurements, the optimal sensor placement is recommended to mount sensors on car body and bogie masses. Thus, by utilizing 6 DOF train model accounting for bogie pitching/yawing motion, rail track profile can be

estimated more precisely.

In summary, this dissertation proposes and realizes an inverse analysis scheme for the railway track profile estimation from in-service vehicle response measurements. The results obtained from numerical analyses and real field experiments exposed that the recommended, data assimilation ASKF method is efficient for condition assessment of local railway track lines with satisfactory correctness.