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学位論文内容の要旨

The deterioration of the aging infrastructures has become a global problem in recent decades, which threatens the public safety. To solve the above problem, researches on structural health monitoring (SHM) and structural damage detection (SDD) have been carried out all over the world. Researchers have made large amounts of efforts in the development of vibration-based SDD methods based on the theories of dynamics and signal processing.

In this thesis, an attempt on SHM has been made on a ballasts concrete railway bridge. By performing a series of vibration experiments, obvious variations on modal parameters have been found. The variations on the modal parameters show difficulties of SHM, which need to be overcome. The difficulties can be summarized as follows: (1) the effects of environmental variation and other uncertainties to the structural dynamic behavior, (2) low efficiency of using the large amounts of monitoring data.

In recent years, the rapid development of Deep Learning technology shows obvious advantages in many fields, such as object detection, medical science, and so on. Firstly, it is a pure data-driven method. By using Deep Learning technology, functions can be generated to link the input data to the results automatically, with no need of any domain knowledge. Secondly, large amounts of data can be used efficiently in the process of training a network.

Therefore, in this thesis, a vibration-based structural state identification method by using 1-D convolutional neural networks (CNNs) has been proposed. The proposed method aims to overcome the difficulties as introduced in the second paragraph by adapting the Deep Learning technology in the civil engineering field to solve the SHM problems.

By using the proposed 1-D CNNs, functions linking the raw vibration data and structural states can be established. Those 1-D CNNs are developed to identify tiny local structural changes, and are validated on actual structures. Databases of structural vibration response are established based on a T-shaped steel beam (in lab), a short steel girder bridge (in test field), and a long steel girder bridge (in service) to validate the performance of the proposed 1-D CNN. The complexities of data in above 3 databases increase progressively. The raw acceleration data are not pre-processed and are directly used as training and validation data.

The well-trained CNNs almost perfectly identify the locations of the small local structural changes, demonstrating the high sensitivity of the proposed CNN to tiny changes in actual structures. The capacity of determining the boundary between data in different structural states is also shown clearly.

Subsequently, to explore the mechanism of the proposed 1-D CNN, the convolutional kernels and outputs of the convolutional and max pooling layers are visualized and analyzed. The effectiveness of the CNN is also proved by visualizing the variation of data structure in each layer of the CNN by the T-SNE method.

Furthermore, to examine the capacity of identify untrained structural changes of the proposed CNN, two rounds of robustness tests of the CNN models are carried out. The results show low capacity of the classification CNN model to identify local structural changes in untrained locations.

Finally, to improve the robustness of the CNN identifying local structural changes in untrained locations, a regression CNN model is proposed with the updated encoding of the label and the output layer of the CNN. Comparing to the classification CNN models, higher robustness is obtained in the regression CNN model. Moreover, a deep network with multi-convolution blocks and multi-task outputs is proposed to further improve the robustness of identifying local structural changes in untrained locations. The results show obvious increase in the accuracies of the network to identify untrained local structural changes.

Overall, the expected contributions will be two-folds. For academy, the results of the study demonstrate the feasibility and rationality of using Deep Learning technology to solve SHM and SDD problems in civil engineering field. The potential of developing new Deep-Learning-based SHM and SDD schemes are also shown. For the society, the proposed research will boost the development of technology that guarantees human's daily safety.

論文審査結果の要旨

老朽化インフラへの対策は世界的な課題であり、これまで構造工学分野でSHM(Structural Health Monitoring)に関する研究が盛んに行われてきた。一方、近年では数理データ科学の工学的問題への応用が期待されている。本論文では、まず従来の手法で一連の橋梁振動測定を行い、温度変化や凍結により固有振動数などが変動することを確認した。損傷が無くてもこれらの指標が変動することがSHMの課題であり、また、大量の測定データを効率的に処理する必要性が示された。そこで、振動データに対する畳み込みニューラルネットワーク（CNN）を用いた構造状態同定法を提案した。実験室のT形鋼梁、実験場の鋼桁橋、さらに実橋梁で振動データを取得したが、いずれでもCNNにより構造変化を表わす錘の位置をほぼ完全に同定した。このCNNのメカニズムを明らかにするために、各データ構造を視覚化しその有効性を確認した。さらに未訓練の構造変化の同定能力や温度変化に対する性能変化を調べるための性能試験を実施した。その結果、CNNの分類精度は低下したが、訓練データの継続的更新や回帰CNNモデルにより性能が改善することを確認した。

以上より本論文は、振動データにディープラーニング技術を適用した新たな構造状態同定法の適用性を実証的に示した。このことは、インフラの点検技術であるSHMの実現可能性を大きく向上させると同時に、数理データ科学の実問題への応用として時宜にかなった好事例を示すものであり、維持管理工学の発展に貢献する。よって、申請者は本論文により北見工業大学博士（工学）の学位を授与される資格がある者と認める。