様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　６ 年　６ 月 ２１ 日現在

機関番号：１４３０１
研究種目：若手研究
研究期間：2021～2023
課題番号：２１Ｋ１４２８４

研究課題名（和文）カルマンフィルターを活用した免震・制振装置の非線形復元力推定法と実記録による検証

研究課題名（英文）Real-time hysteresis identification in controlled structures based on restoring force reconstruction and Kalman filter

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交付決定額（研究期間全体）：（直接経費）　　3,500,000円

研究成果の概要（和文）：本研究では、地震時の局所的な免震・制振装置の非線形履歴挙動を建物内の限られた計測箇所の観測データからリアルタイムに推定する手法の開発を行った。非線形モデルやパラメータを事前に用意せずに、カルマンフィルターに基づく復元力を拡大状態量として推定できることを理論的・実験的に確認した。更に、ニューラルネットワークを用いたデータ駆動型モデルを融合させ、安定性が高い推定手法も構築した。各種の免震・制振構造物の数値例と振動台実験において、提案手法は観測点数が少なくても高い推定精度を発揮することを明らかにした。

研究成果の学術的意義や社会的意義
日本においては、地震が災害リスクとして主要な位置を占めており、構造モニタリング技術は地震対策の一環としてさらなる発展が期待できる。現在の構造モニタリングの解析手法は、主に固有振動数、モード形状、減衰比のような建物全体の振動特性の変化を評価する手法が多いが、構造物の非線形性や局所的な損傷状況を把握するのには適していない。本研究では、免震・制振装置の非線形履歴挙動をリアルタイムに推定する方法を確立し、それによって装置の損傷を検知できる可能性を示した。これらの技術は、居住者や建物の施設管理者向けの建物の健全性や被害状況を瞬時に把握する基盤技術となる得るものである。

研究成果の概要（英文）：This study develops a new framework for real-time identification of the nonlinear hysteric behavior of seismic response-controlled structure using limited observation data. First, a pure Kalman filter algorithm is employed and it is proved that the additional augmentation of the restoring forces as state variables acts as the role of Tikhonov regularization. Furthermore, to address the numerical instability issues, a physics-deep neural network model and unsupervised autoencoders are integrated with the Kalman filter equation respectively. Numerical examples of various seismic isolation and vibration control structures, as well as shaking table experiments show that the improved methods have high estimation accuracy and stability, even with limited number of measured data.

研究分野：構造工学

キーワード：復元力　カルマンフィルタ　深層学習　オートエンコーダー　ニューラルネットワーク　履歴特性

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Structural health monitoring is a crucial technique that allows to monitor changes and estimate damages for building structures after seismic events and becomes more and more important in Japan. However, current data analysis methods for structural monitoring are mainly based on the evaluation of changes in the vibration characteristics of the whole building, such as natural frequencies, mode shapes and damping ratios. Although these existing evaluation indices are suitable for assessing the overall characteristics of a structure, they are not suitable for understanding the behaviors of the seismic response-controlled structure, which shows strong nonlinear properties locally.

Existing approaches for local hysteresis identification normally treat it as an inverse problem where the objective function is typically defined as the weighted least-squares of the misfit between the measured data and the predicted data, and the model parameters for a certain prescribed hysteretic model should minimize the objective function. However, these algorithms not only require prohibitively high computation cost due to the repeated solution of a large-scale nonlinear and possibly non-smoothing differential equation, but also rely on the prescribed hysteresis models which might introduce model errors for the identification. Consequently, developing a real-time, model free hysteresis identification algorithm with indirectly observed and noisy measurement data for practical seismic damage estimation problem remains a significant challenge.

２．研究の目的

In order to obtain a cost-effective as well as widely applicable method for hysteresis identification, this paper develops a completely new hysteresis identification framework where rather than identifying the model parameters, the restoring forces of hysteretic components are reconstructed and the original nonlinear hysteresis identification process is converted to a linear system estimation problem. In this way, the proposed framework aims to achieve several key advantages,

(1) Hysteresis identification is fulfilled through restoring force (and hysteretic displacement) reconstruction. Therefore, a search for the optimal values of the hysteretic model parameters is avoided and so is the a priori knowledge of the hysteretic models. Thus, the proposed framework also works for the general situations where the hysteretic models do not need to be known.

(2) The proposed framework does not involve the nonlinear hysteretic models and then, a linear system equation with the unknown restoring forces is undertaken. For large-scale problems, linear system estimation can be solved much more efficiently than nonlinear and possibly non-smoothing system estimation. Thus, the proposed framework shall be efficient.

(3) The proposed framework identifies restoring force and the hysteretic displacements using indirectly observed measurement data, which means that the framework is employed when restoring force and the corresponding hysteretic displacement are not directly accessible, but some other quantities, e.g. floor accelerations at several stories, are measured.

３．研究の方法

The proposed hysteresis identification framework is being developed in three stages:

(1) First, a pure Kalman filter algorithm is adopted for restoring force reconstruction and it is shown that the additional augmentation of the restoring forces as state variables acts as the role of Tikhonov regularization. Due to the regularization effect, an optimal covariance matrix for the process noise of the restoring forces is selected by the L-curve method. It is noteworthy that numerical instabilities may happen when using the pure Kalman filter algorithm, since a priori observability and identifiability of the dynamic system with a particular set of measured data should be carefully checked.

(2) To overcome the numerical instabilities encountered in the previous stage, the Kalman filter algorithm is embedded into a deep learning framework, where the linear state equation and the obscure nonlinear hysteric behavior are smoothly combined through a physics-deep neural network (DNN) hybridized integration time-stepper. By utilizing neural networks to establish a data-driven model for hysteresis, the identified nonlinear hysteric behavior is still model free and significant progress is made in overcoming the numerical instabilities. However, the necessity to measure both the restoring force as well as the corresponding displacement for training the neural network makes this algorithm impractical for real-world structural health monitoring system applications.
(3) Since the effectiveness of data-driven hysteric model based on neural networks has been proved in stage 2, finally, we proposed a computationally practical approach for recovering the local hysteric behavior based on the combination of Kalman filter and unsupervised autoencoders. In the autoencoder, the measurement data is encoded and the feature of its noise level is first learned in the space of the latent variable. Then another neural network is used to predict system full states with ground motion and latent variable as input. These predictions are used for measurement data reconstruction by a physical guided decoder with the linear state equation from the Kalman filter. We demonstrated the ability of the proposed method to estimate the full states of the dynamic system with limited measurement data as well as its ability to overcome numerical instabilities successfully.

４．研究成果

For the above three stages, various numerical examples (single-story and multi-story structures) as well as experiments tests (base-isolated structure and structure with dampers) have been conducted to validate the effectiveness and robustness of the proposed identification framework. The algorithm has also been verified using real-measured field data. Due to the confidentiality agreement, the results are not presented herein.

(1) Stage 1: pure Kalman filter algorithm

To illustrate the application of the present hysteresis identification method, a seven-story shear building as shown in Fig. 1 is concerned. In the case of impulse excitation, the feasibility of the proposed method in identifying different kinds of hysteretic models at different positions of the structure is shown. Besides, the performance of the L-curve method in finding an appropriate process noise covariance for the augmented state is fairly verified. Next, the effects of different levels of amplitude and varying spectral content of the external force on the proposed method are investigated through harmonic excitation. Last, the robustness of the proposed method to different initial conditions is studied using earthquake excitation. Special attention is also given to the measurement requirement to provide stable results.

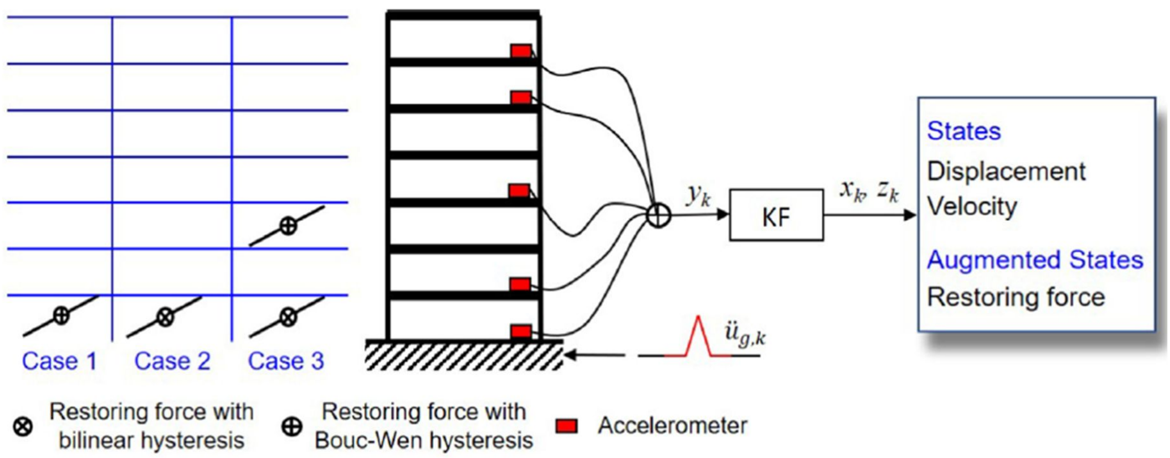


Fig.1 Schematic view of the seven-story shear building

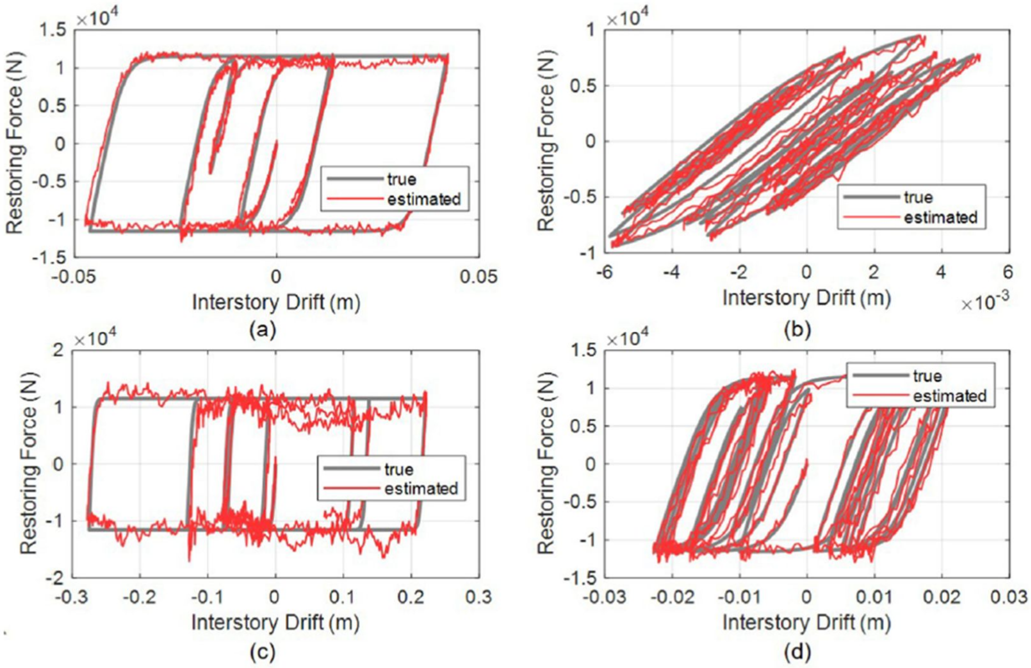
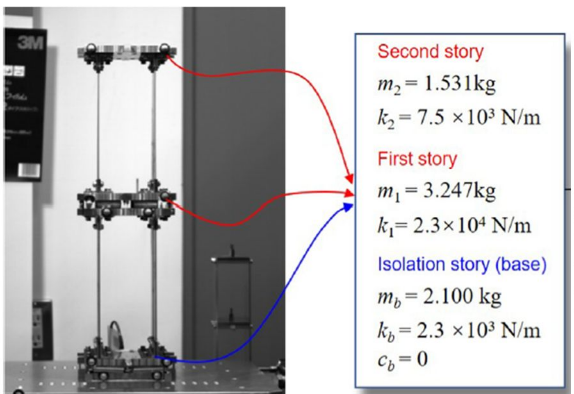


Fig. 2 Hysteresis identification results based on the pure Kalman filter algorithm

Furthermore, dynamic tests of a two-story base-isolated shear structure are conducted at the structural laboratory in Kyoto University to validate the proposed real-time hysteresis identification method. Fig. 3 shows details of this base-isolated shear structure including each story's stiffness and mass. The nonlinear hysteretic behavior which serves as the seismic isolator of the structure is provided by the frictional interfaces of a slider in the isolation story. Clearly in Fig. 4, the identified hysteretic loop fits reasonably well with the reference/experimental hysteretic loop.



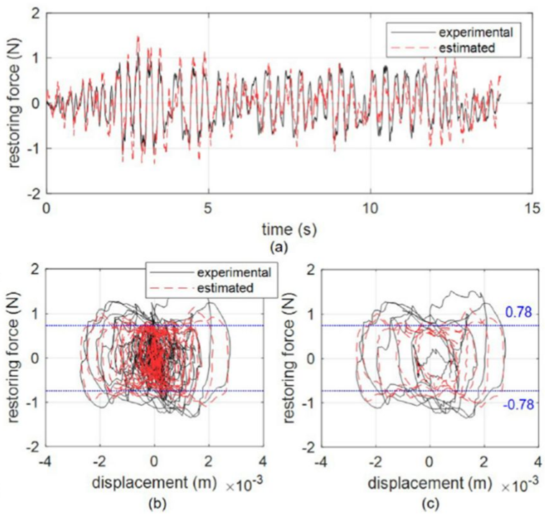


Fig. 3 Laboratory test setup

Fig. 4 Identification results

(2) Stage 2: Kalman filter + deep neural network

The proposed identification framework is examined by a numerical example of a base-isolated seven story shear building and dynamic tests of a single-degree-of benchmark structure equipped with a tuned inter eddy current damper, which was conducted at the structural laboratory in Tohoku University. Experimental setup and identification results of Eddy current damping system are shown in Fig. 5 and Fig.6.

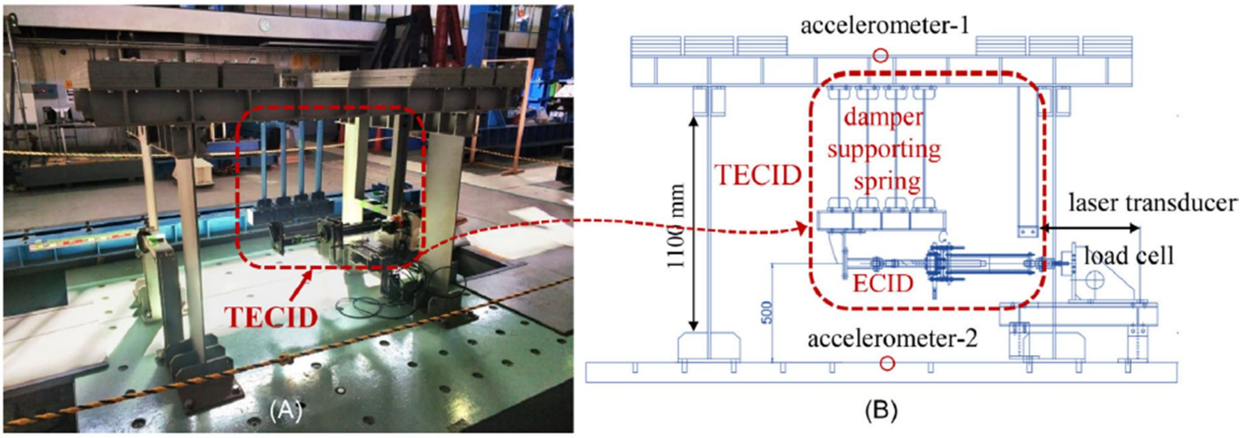


Fig.5 Photograph of the experimental specimen with eddy current damper

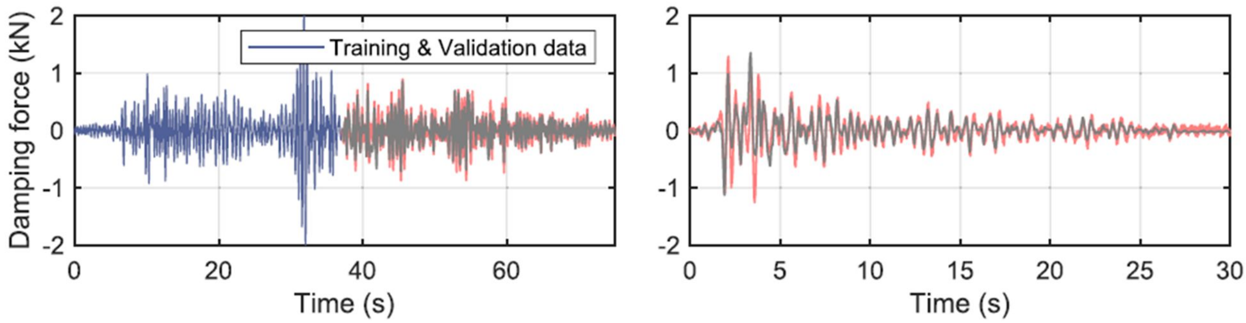


Fig.6 Training and prediction results of the proposed algorithm

(3) Stage 3: Kalman filter + Autoencoder

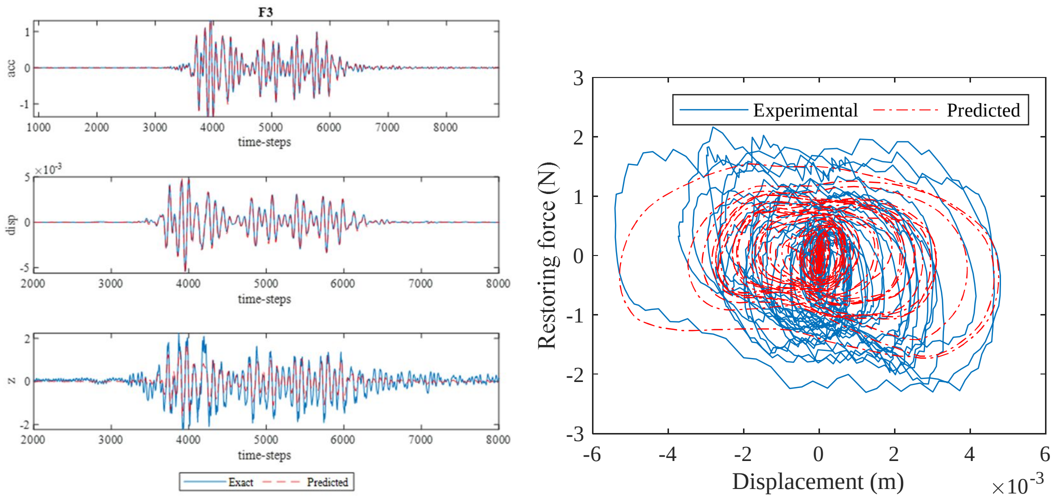


Fig.7 Identification results using the same laboratory test but with less data compared to Stage1

In this stage, the proposed identification algorithm is verified using a numerical example of a multi-story building with dampers on each floor. Additionally, the same experimental test in stage 1 is utilized. The difference from stage 1 is that only the acceleration measurement is used in stage 3, whereas the second story's measured displacement was also necessary for numerical stability in Stage 1. The results in Fig.7 demonstrate that the proposed method effectively identifies the hysteretic behavior stably from limited data.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　0件）

１．著者名 Guo J, Enokida R, Li D, Ikago K.	４．巻 -
２．論文標題 Combination of physics-based and data-driven modeling for nonlinear structural seismic response prediction through deep residual learning	５．発行年 2023年
３．雑誌名 Earthquake Engineering & Structural Dynamics	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1002/eqe.3863	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Wang Li、Guo Jia、Takewaki Izuru	４．巻 150
２．論文標題 Real-time hysteresis identification in structures based on restoring force reconstruction and Kalman filter	５．発行年 2021年
３．雑誌名 Mechanical Systems and Signal Processing	６．最初と最後の頁 107297～107297
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ymssp.2020.107297	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Guo Jia、Wang Li、Fukuda Iori、Ikago Kohju	４．巻 167
２．論文標題 Data-driven modeling of general damping systems by k-means clustering and two-stage regression	５．発行年 2022年
３．雑誌名 Mechanical Systems and Signal Processing	６．最初と最後の頁 108572～108572
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ymssp.2021.108572	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計3件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Jia GUO
２．発表標題 Combination of physics-based and data-driven modeling for nonlinear structural seismic response prediction
３．学会等名 The 15th World Congress on Computational Mechanics & the 8th Asian Pacific Congress on Computational Mechanics（国際学会）
４．発表年 2022年

1．発表者名 郭 佳
2．発表標題 物理シミュレーションと人工知能を融合した構造物の非線形地震応答推定手法
3．学会等名 第66回理論応用力学講演会
4．発表年 2022年

1．発表者名 郭 佳
2．発表標題 Combination of physics-based and data-driven modeling for nonlinear structural seismic response prediction
3．学会等名 第27回計算工学講演会
4．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関