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燃料電池等利用の飛躍的拡大に向けた共通課題解決型産学官連携研究開発事業/水素利用等高度化先端技術開発 /交流磁場誘起レーザー変位計を用いた金属異物非接触マイクロ断層検出システムの開発

団体名：名城大学

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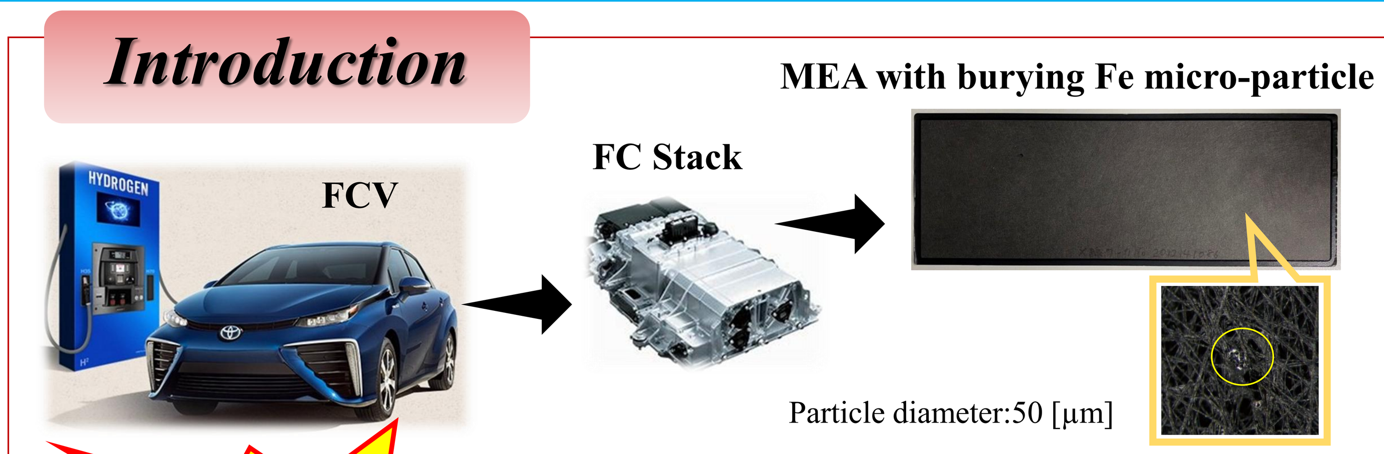
Introduction

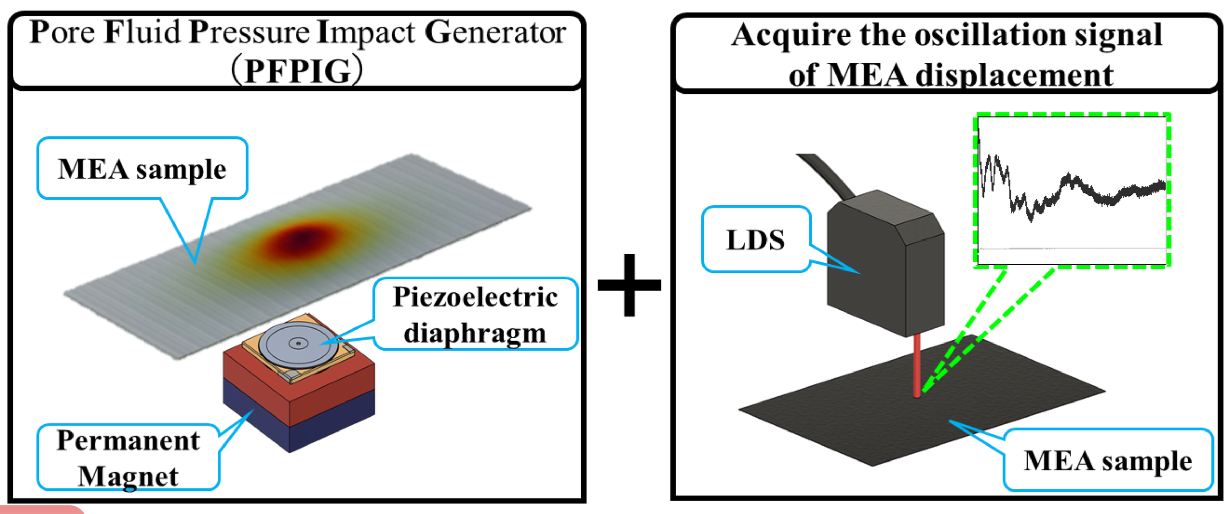


In recent years, fuel cells have been expected to be a promising technology for achieving ***"Carbon Neutrality"***. In the manufacturing process of MEA, the main component of fuel cell, there remains the problem of metallic foreign micro-particles contaminating MEA, reducing not only the power generation efficiency but also safely utilizing hydrogen. X-ray inspection is commonly used as a method for detecting metallic particles, which has serious industrial problems such as high cost and long inspection time. Therefore, there is a need for a simple system that can automatically detect the presence or absence of metallic foreign matter in real time.

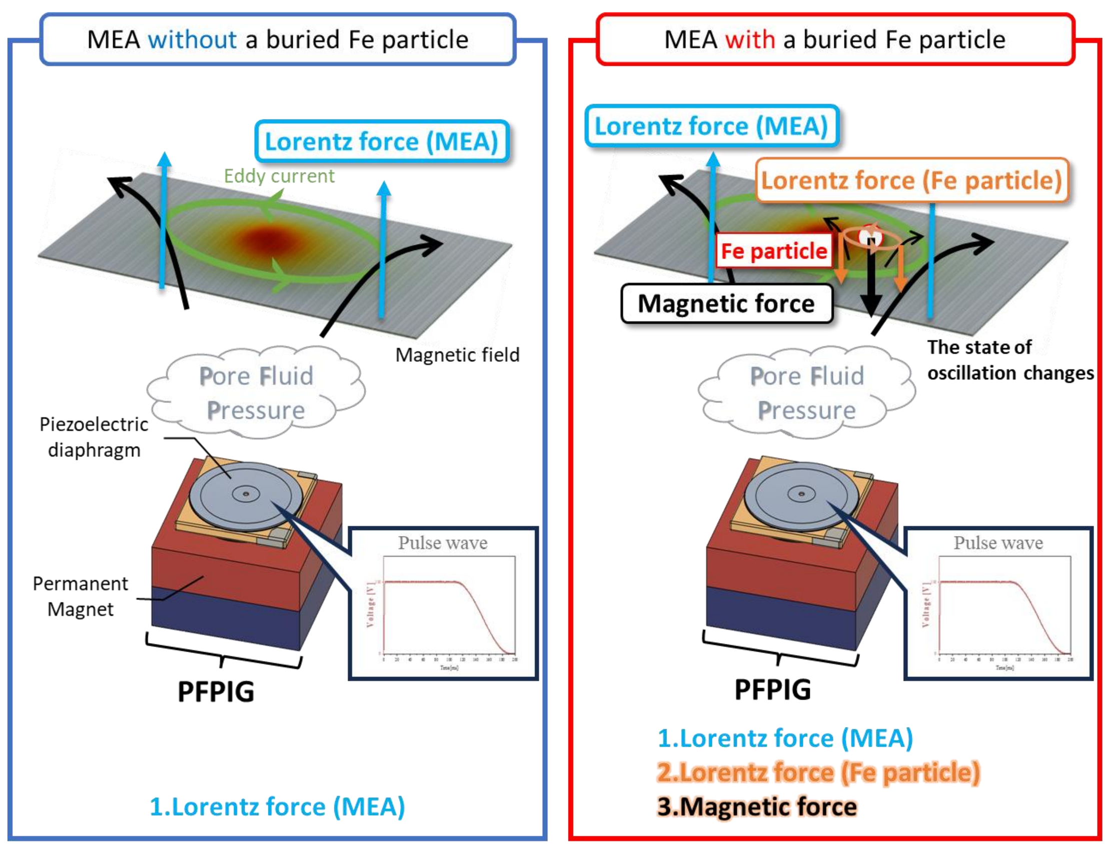
Objectives

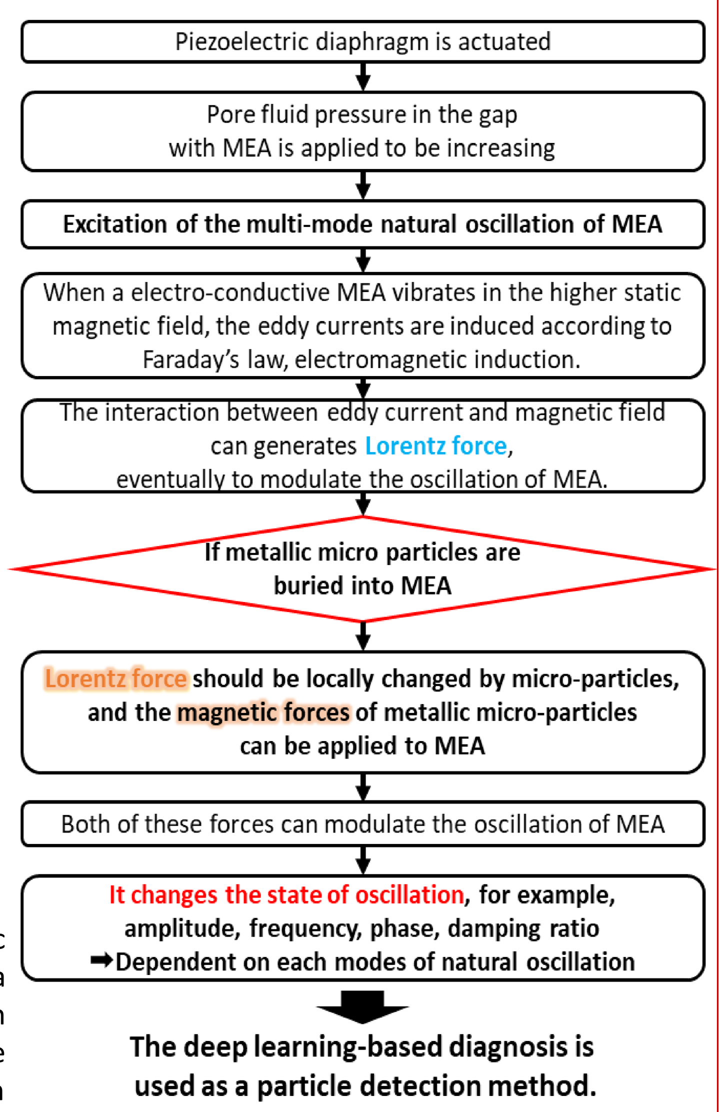
A rapid and automatic diagnosing system of metallic micro-particles, namely PFPA-LDS (Pore Fluid Pressure Assisted - Laser Displacement Sensor) under static magnetic field is proposed and constructed. PFPA-LDS is based on a vibration testing technique for contaminants Inspection, which is attributed to both eddy current Lorentz force and magnetic force.

- **non-contact** ○
- **cost** ○
- **inspection time** ○
- **detectable particle size** ○



Proposed Method PFPA-LDS



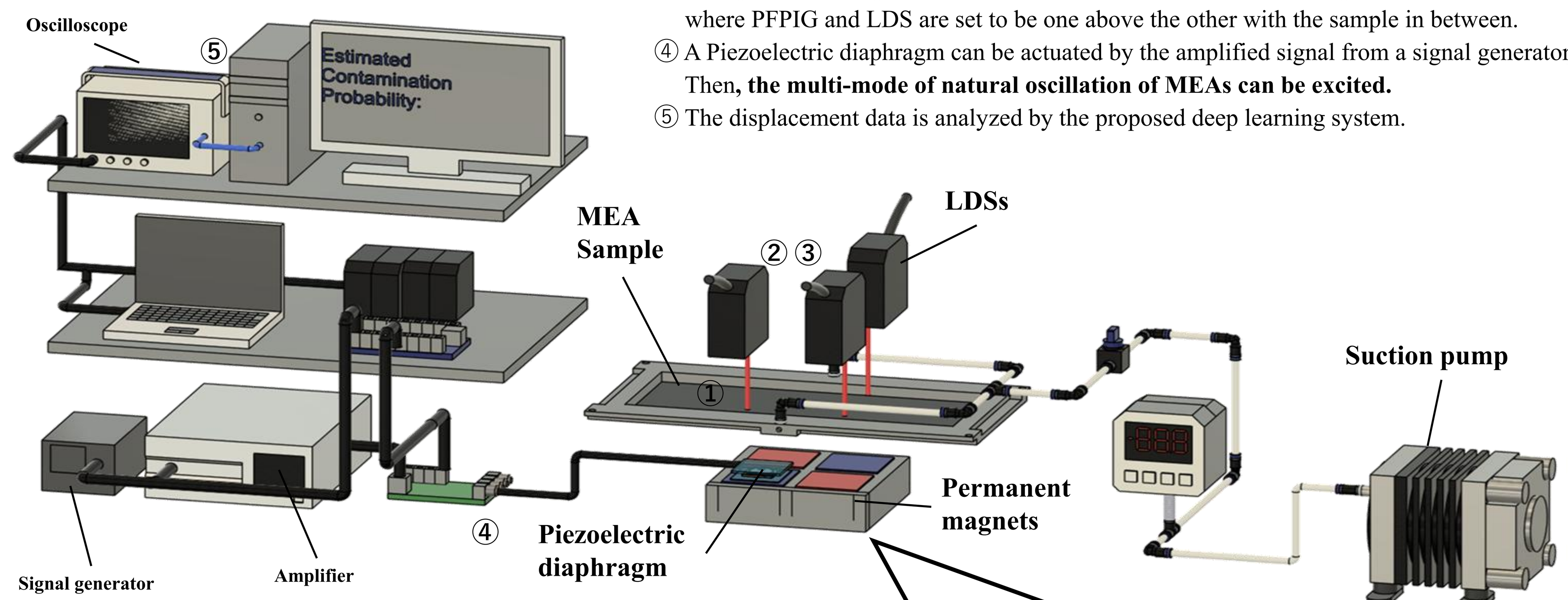


Pore Fluid Pressure Impact Generator, PFPIG, is constructed by a Piezoelectric diaphragm actuator placed on a permanent magnet, where is installed just below a MEA sample, then it can excite the natural oscillation by the pulsed actuation. When an electro-conductive MEA vibrates in the static magnetic field, the eddy currents are induced according to Faraday's law, electromagnetic induction. The interaction between eddy current and magnetic field can generates Lorentz force. When metallic micro-particles are buried into MEA, Lorentz force should be locally changed by micro-particles. Eventually, both of Lorentz forces and magnetic forces, including pore fluid pressure, can modulate the oscillation of MEA. The presence or absence of metallic foreign micro-particles can change the state of oscillation, for example, amplitude, frequency, phase, damping ratio, *e.t.c*, which is dependent on each mode of natural oscillation.

Experiment

◎ Schematic view of PFPA-LDS system

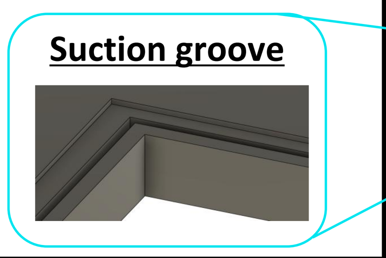
① 2×2 units of PFPIG, and a MEA sample is installed horizontally above PFPIG.
② The detection instruments of oscillation signal, LDSs are positioned above a sample.
③ A single LDS is aligned perpendicularly to the central axis of a single PFPIG, where PFPIG and LDS are set to be one above the other with the sample in between.
④ A Piezoelectric diaphragm can be actuated by the amplified signal from a signal generator. Then, **the multi-mode of natural oscillation of MEAs can be excited.**
⑤ The displacement data is analyzed by the proposed deep learning system.



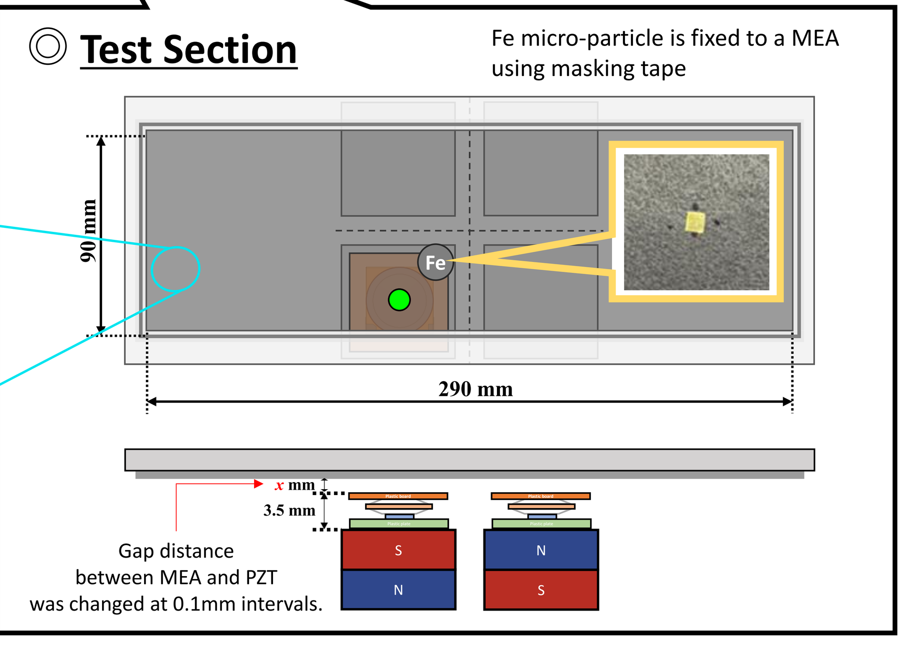
Boundary Conditions

All sides of sample boundaries are installed on the suction groove machined on a sample holder, where it was fixed by negative pressure 78 [kPa] by a vacuum pump.

Condition	Param
Suction groove width	1 [mm]
Negative pressure	-78 [kPa]
Intake volume	74 [L/min]



◎ Test Section



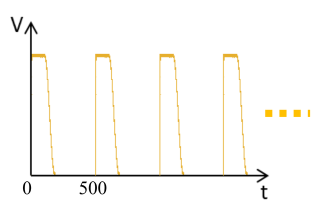
MEA sample Conditions

- MEA samples were prepared in rectangular sizes of 300 [mm] and 100 [mm].
- The particle diameter is about 150 [μm] and is placed on the inspection area of the PFPIG unit.
- 16 sheets of MEAs were applied with the presence or absence of Fe micro-particles.
- The MEA sample was reinstalled three times.

Piezoelectric diaphragm driving Conditions

- The piezoelectric diaphragm is moved upward to a sample and then kept position there.
- The piezoelectric diaphragm is repeatedly driven 20 times at 500 [ms] intervals.
- This movement can generate a pulse-like pore fluid pressure to excite the multi-mode of natural oscillation of MEA sample.

Condition	Param
Signal type	Step
Voltage	110 [V]
Time width	110 [ms]



Measurement Conditions

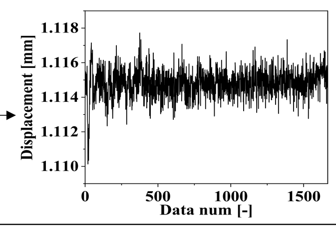
The oscillation signal of displacement was detected by LDS directly above the PFPIG unit and then was acquired as 50 thousand points of time series data by oscilloscope.

Condition	Param
Measurement unit	Bottom Left Center
Sampling rate	100000 [Hz]

Deep Learning Model

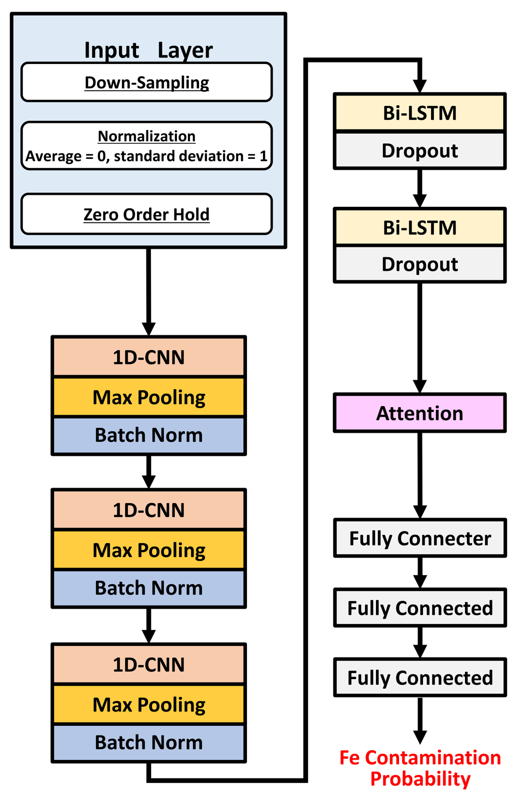
This DL model consists mainly of 1D-CNN and Attention-LSTM, both of which networks are directly connected to extract the oscillation features from obtained signals of the excited multi-mode of natural oscillation.

Input data



The oscillation state has highly sensitivity on the gap distance between MEA and PFPIG. The oscillation signal, the raw data, was converted to the distance between the MEA and the Piezoelectric diaphragm, directly related to the experimental geometry. The converted data were prepared as the input data.

1D-CNN is composed of three-layers with the hierarchical changes in respective hyper-parameters of filter size and the number of filters. 1D-CNN is mainly specialized in the frequency domain analysis, and it is thought that the oscillation features of each mode are extracted by multiple filters.



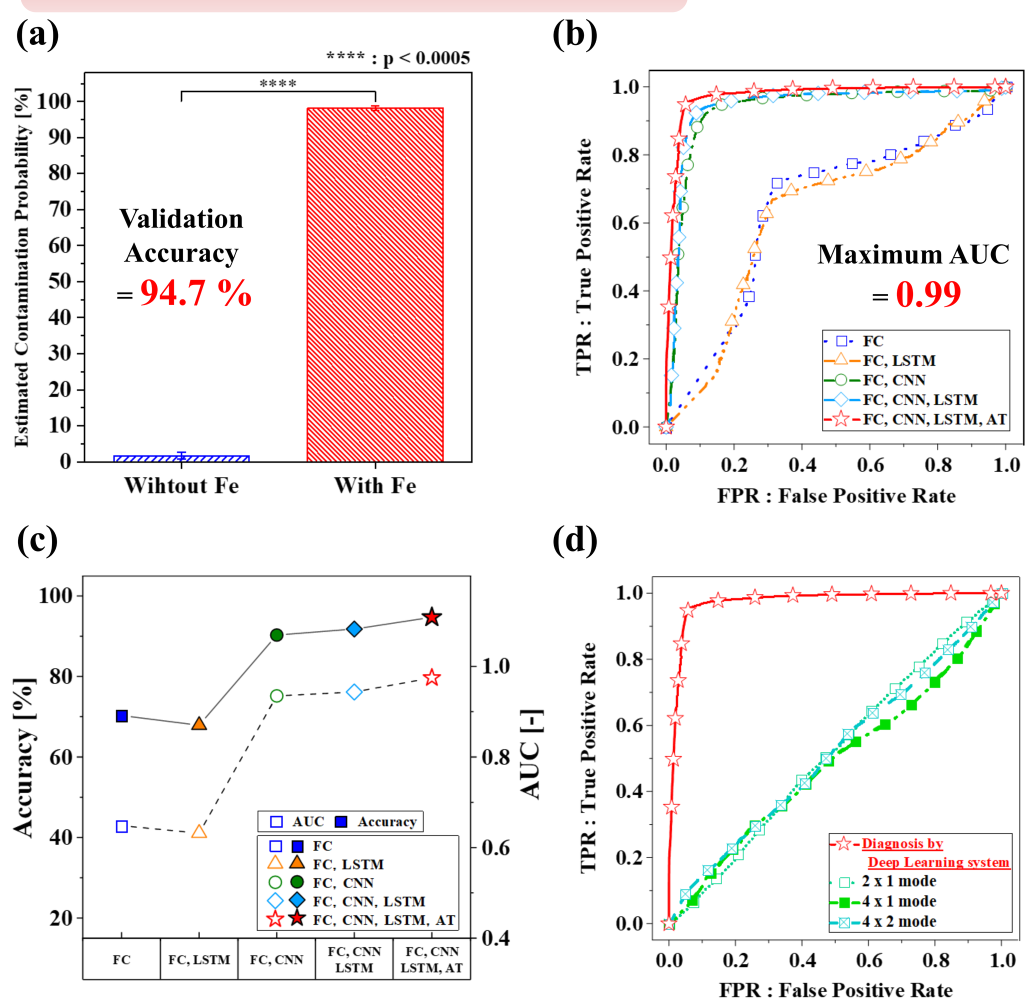
LSTM is mainly specialized in the time-domain analysis and use LSTM-cells with memory to extract time-dependent features from time-series data.
Dropout is followed by LSTM to prevent the overfitting.

Attention layer calculates weights for each element of the input signal, this can emphasize important parts of the input data according to these weights, to extract relevant features changes such as the phase and damping ratio.

Three fully-connected layers, with hierarchical changes in the number of units can estimate the contamination probability using a sigmoid function.

Two of the three dataset were used as the teaching data of the proposed deep learning system, while the other one was prepared as the test data to validate the accuracy.

Result & Discussion



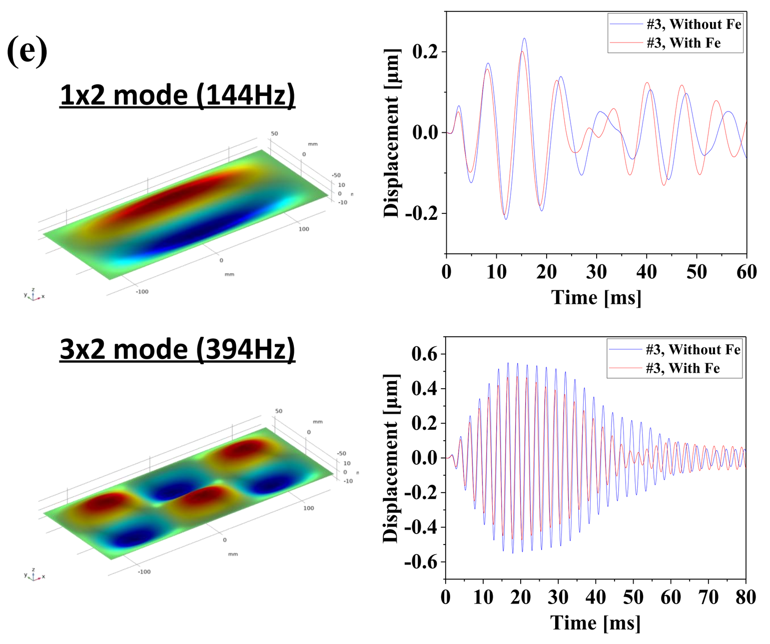


Figure (a) shows the estimated contamination probability corresponding to the existence of Fe micro-particles buried in MEA. There appears to be more than 90% difference in the contamination probability between presence and absence of Fe micro-particles, and the standard deviation was suppressed under 1% with validation accuracy approaching to 95%. **Figure (b)** shows a result of ROC analysis, the red curve of **proposed PFPA-LDS** system can indicate the high accuracy with AUC=0.99, signifying excellent discriminatory power between positive and negative classes. Additionally, **Figure (c)** shows the dependency of accuracy and AUC on DL models. **1D-CNN** is found to be particularly effective in extracting frequency-dependent features for each oscillation mode. **Attention-LSTM** is found to have a high potential to extract accented time-dependent features such as the phase and damping of each oscillation mode signal. **Figure (d)** shows the comparison with the standard phase analysis of each modes as ROC curves, apparently resulting in the significant enhancement of classification. **Figure (e)** shows examples of time series oscillation data corresponding to two different natural oscillation modes excited by the pore fluid pressure. It can be seen that the amplitude, frequency, phase, and damping ratio are changed depending on the presence or absence of foreign objects. In addition, there seems to be a significant difference between 1x2 mode and 3x2 mode. Therefore, the oscillation state has different dependencies on each modes of natural oscillation.

Conclusions

We present the proposed system, PFPA-LDS, based on a vibration testing technique for contaminants inspection, which is attributed to both eddy current Lorentz force and magnetic force, additionally pore fluid pressure. The instrumented DL model, which is directly connected to 1D-CNN and Attention-LSTM, can extract the oscillation features to detect metallic micro-particles from the obtained signals of the excited multi-mode of natural oscillation. In conclusions, the proposed method has an effective potential as an automatic diagnostic system of metallic micro-particles buried into MEA.

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