The efforts for the interpretability of deep models

Investigating the interpretability of deep models is a meaningful research direction. To explore the learning ability of the model as thoroughly as possible, the following works are conducted.

1. The vibration signals collected in the experiment often are masked by electrical noise and coupling interference from other parts. To better understand the signal representation at different speeds learned by deep model, we followed the literature [*Yunjia Dong. Investigation of dynamic simulation and transfer learning based fault diagnosis method for rolling element bearings. MS thesis. Harbin Institute of Technology, 2019.*] to establish a dynamic model for the bearing, because the simulation data can significantly reflect the bearing fault characteristics, which is conducive to reducing the interference on the model visualization. The essential parameters for establishing the differential equations of bearing dynamics are listed as follows.

Table 1.1 Bearing geometric parameters and fault frequency.

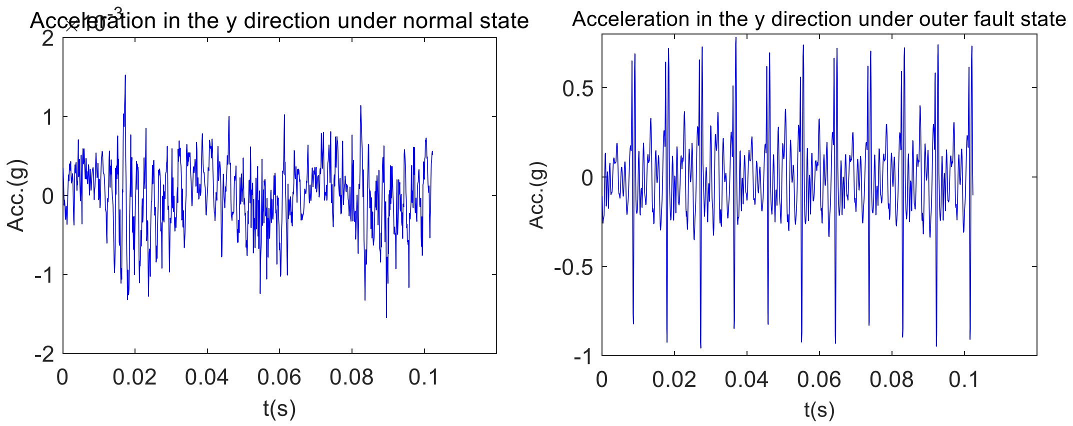
Parameter	Value
Pitch diameter D_m *(mm)*	39.04
Number of rolling elements N_b	9
Ball diameter d_b (mm)	7.94
Contact angle α (°)	0
Fault frequency of the inner race f_{in}	5.42 f_r
Fault frequency of the inner race f_{out}	3.58 f_r
Fault frequency of the ball f_{ball}	4.71 f_r

Note: f_r denotes the rotating frequency of the shaft and the bearing inner.

Table 1.2 Dynamic simulation parameters of the bearing.

Parameter	Value	Parameter	Value
Mass of inner race-shaft m_{in} (kg)	50	Contact stiffness k_b (N/m)	8.753×10^9
Shaft-connection stiffness k_{im} (N/m)	7.42×10^7	Acceleration of gravity g (m/s^2)	9.8
Shaft-connection damping c_{im} (Ns/m)	1376.8	Fault width L (mm)	0.5
Mass of outer race-bearing seat m_{out} (kg)	5	Fault depth h (mm)	0.5
Bearing seat foundation connection stiffness k_{out} (N/m)	1.51×10^7	Radial clearance c_r (m)	2×10^{-6}

Bearing seat foundation connection damping c_{out} (Ns/m)	2210.7	Eccentricity e (m)	15×10^{-6}



(a) (b)

Fig. 1.1 Vibration signal of (a) normal bearing; (b) bearing with outer race fault.

Fig. 1.1(a) presents the vibration signal of a normal bearing at 1800 rpm, and Fig. 1.1(b) gives the vibration signal of a bearing with an outer race defect at 1800 rpm. Since the environmental noise is not incorporated into the simulation signal, the periodic impulse shocks induced by the outer race defect are evident in Fig. 1.1(b). The bearing dynamics simulation code is available at *https://github.com/LinBo-Team/Support-code/tree/eb5c27e71db6ba9d95d356e1da63c0977c306acf/Bearing%20dynamics%20simulation* for reference (MATLAB version).

2. It is worth noting that the raw vibration samples are not preprocessed and transformed here to enhance the visualization effect of the deep model learning different rotational speed samples, which also facilitates the analysis of the processing process of the deep model for cross-rotational speed vibration signals. The convolution layer output of the deep model is extracted during the training process in Fig. 1.2. At the initial stage of the deep model training, the state representation of the convolution layer output is irregular due to the random initialization of parameters such as the convolution kernel. With the increase of training epoch, the network gradually learns the characteristics of periodic pulses buried in vibration signals. It can be observed from the envelope

spectrum that most of the learned representations are the characteristics of medium and low-frequency bands, and the interference frequency components gradually decrease with the training process of the model.

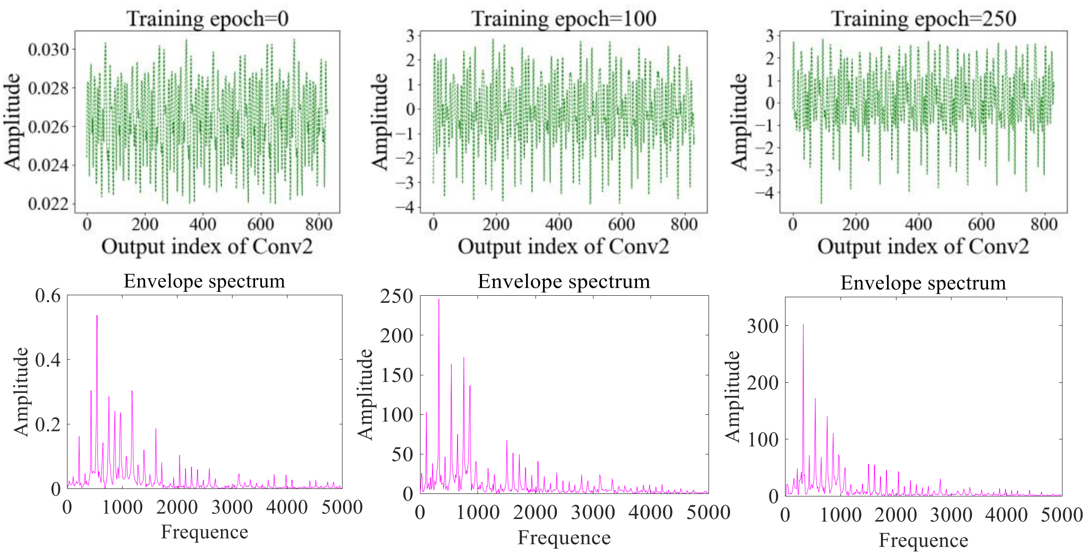
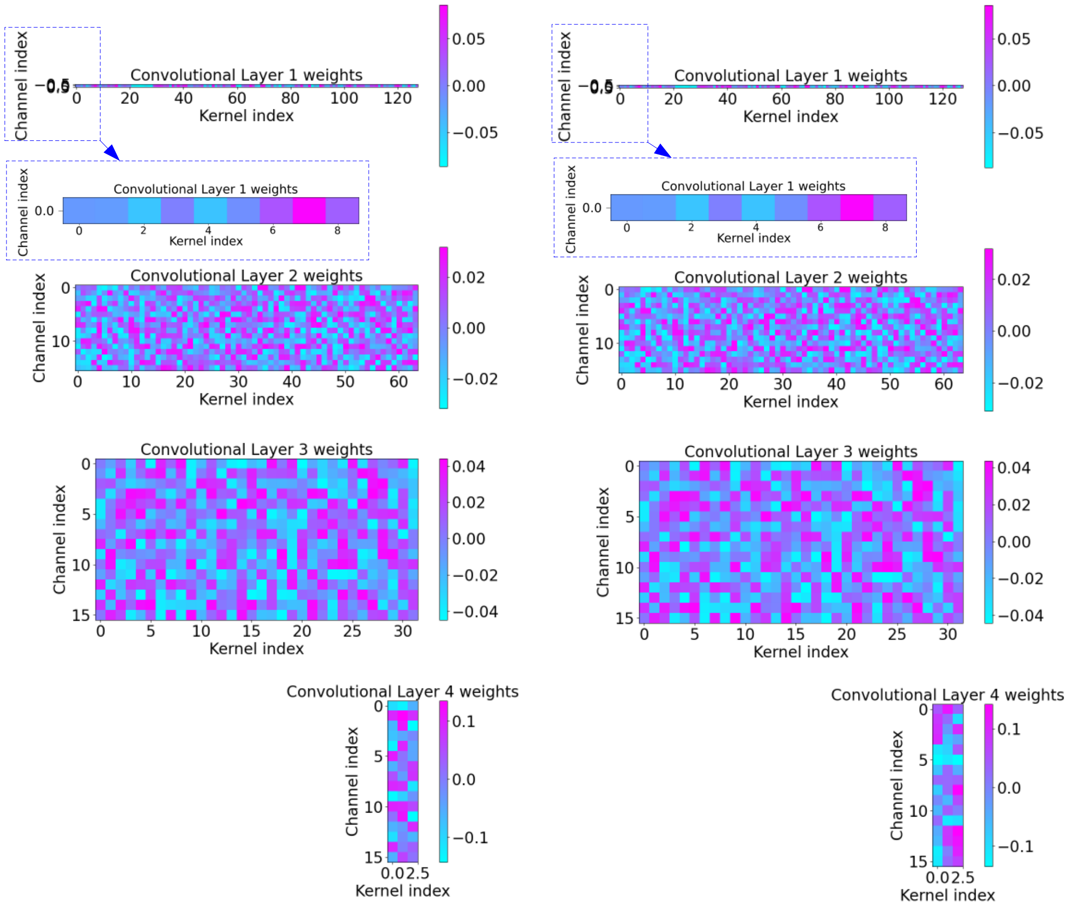


Fig. 1.2 Output visualization of the convolution layer 2.

3. Fig. 1.3 visualizes the convolution weights of the deep convolution network. Fig. 1.3 (a) shows the convolution kernel when the deep model is used to identify the health state of the implanted outer ring fault and the normal bearing under 1800rpm, and Fig. 1.3 (b) depicts the convolution kernel when identifying the health state of the implanted outer ring fault and the normal bearing under 1200rpm.



(a) (b)

Fig. 1.3 Convolution kernel visualization of the deep model under (a) 1200rpm (b) and 1800rpm.

Because the deep model deals with objects that are very similar, such as fault characteristics. The rotational speed mainly affects the pulse impact period. it can be inferred from the figure that for the fault diagnosis tasks at two different rotational speeds, the convolution kernels of the first layer and the second layer of the network are similar, especially the convolution kernel of the first layer. This implies that shallow convolution focuses on the general characteristics of learning tasks. From the third layer and the fourth layer, the convolution kernel weights are quite distinct, especially in the last convolution layer, the weight distribution difference is the most significant. Based on the above reasons, the regularized adaptive weight optimization strategy determines the weight of each working condition adaptively based on the domain loss of the final output of the model.