机器学习期末大作业

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- 专业：计算机科学与技术

实验要求

题目：基于VAE的手写数字生成

实验条件：MNIST手写数字数据集：http://yann.lecun.com/exdb/mnist/ 也可以通过 sklearn，pytorch 和 tensorflow 内置的函数直接下载。该数据集由60000个样本的训练集和10000个样本的测试集组成（生成模型中不需要测试集），规模较大，硬件条件有限的同学可以进行下采样(例如选取6000个样本)后进行建模和训练。

实验要求：

1. 基本要求：利用 pytorch (推荐) 或 tensorflow 等神经网络框架编程实现一个变分自编码器 (Variational Auto Encoder, VAE)；分别采用交叉熵损失 (Cross Entropy Loss) 和L2损失 (MSE Loss) 构建损失函数生成新的手写数字,分析结果并展示生成的手写数字；
2. 中级要求：实现VAE的变分推断(最好是手写推导)，描述VAE的由来以及优缺点；
3. 提高要求：实现任意形式的对VAE进行改进或创新，例如：和其他网络结合或对比（图卷积神经网络(GCN)，生成对抗网络(GAN)，Diffusion Model等）；实现VAE的变种（β-VAE，β-TCVAE等）；修改数据集（例如加噪点，加mask等）以发掘VAE更多的功能；对可视化方法进行创新（例如输出隐变量）......

截止日期：初步定于2023年1月7日

- 以.ipynb形式的文件提交，输出运行结果，并确保自己的代码能够正确运行；
- 可以1-3人为一小组的形式进行提交，提交的文件中需要写明每个小组成员的贡献；
- 发送到邮箱：2120220594@mail.nankai.edu.cn；

小组成员贡献：

2012067黄逸轩：基本要求、中级要求、报告框架搭建

2012628程佳诺：提高要求、报告汇总修改

目录结构：

ipynb文件正常运行后，目录结构应如下：

```
|   VAE.ipynb
|
├─.ipynb_checkpoints
|      VAE-checkpoint.ipynb
|
├─advanced
|  ├─beta_VAE
|  |  ├─samples_mse_beta2
|  |  ├─samples_mse_beta3
|  |  └─samples_mse_beta4
|  └─modified dataset
|      ├─samples_mse_mask
|      └─samples_mse_noise
├─data
|  └─MNIST
|      └─raw
|            t10k-images-idx3-ubyte
|            t10k-images-idx3-ubyte.gz
|            t10k-labels-idx1-ubyte
|            t10k-labels-idx1-ubyte.gz
|            train-images-idx3-ubyte
|            train-images-idx3-ubyte.gz
|            train-labels-idx1-ubyte
|            train-labels-idx1-ubyte.gz
└─primary
    ├─samples_ce
    └─samples_mse
```

其中，data文件夹中为pytorch下载的数据集，primary文件夹为基本要求部分生成结果，包含交叉熵损失结果samples_ce文件夹和MSE损失结果samples_mse；advanced文件夹为提高要求部分生成结果，包括beta_VAE实现结果beta_VAE文件夹，下含samples_mse_data2/3/4文件夹，表示以mse构造损失函数超参数beta取值为2/3/4时的运行结果；修改数据集实现结果modified dataset文件夹，下含samples_mse_noise表示以mse构造损失函数处理方法为加噪点的运行结果与samples_mse_mask表示以mse构造损失函数处理方法为加mask的运行结果。每一个最内层文件夹中包含15个reconst和15个sampled图片，为解码结果。

一份成功的输出结果：

sampled.png：

reconst.png:

基本要求

本小组选择使用pytorch框架来辅助实现VAE模型

导入需要的包

```
In [1]:  import os
         import torch
         import torch.nn as nn
         import torch.nn.functional as F
         import torchvision
         from torchvision import transforms
         from torchvision.utils import save_image
```

配置CPU或者GPU

```
In [2]:  device = torch.device('cuda' if torch.cuda.is_available() else 'cpu')
```

创建目录保存生成的图片

```
In [3]:  sample_dir_ce = 'primary/samples_ce'
         sample_dir_mse = 'primary/samples_mse'
         if not os.path.exists(sample_dir_ce):
             os.makedirs(sample_dir_ce)
         if not os.path.exists(sample_dir_mse):
             os.makedirs(sample_dir_mse)
```

超参数设置

```
In [4]:  image_size = 784    #图片大小
         h_dim = 400
         z_dim = 20
         num_epochs = 15    #15个循环
         batch_size = 128    #一批的数量
         learning_rate = 1e-3    #学习率
```

获取数据集

```
In [5]:  dataset = torchvision.datasets.MNIST(root='./data',
                                              train=True,
                                              transform=transforms.ToTensor(),
                                              download=True)
```

```
Downloading http://yann.lecun.com/exdb/mnist/train-images-idx3-ubyte.gz
Downloading http://yann.lecun.com/exdb/mnist/train-images-idx3-ubyte.gz to ./data\MN
IST\raw\train-images-idx3-ubyte.gz
  0%|          | 0/9912422 [00:00<?, ?it/s]
Extracting ./data\MNIST\raw\train-images-idx3-ubyte.gz to ./data\MNIST\raw

Downloading http://yann.lecun.com/exdb/mnist/train-labels-idx1-ubyte.gz
Downloading http://yann.lecun.com/exdb/mnist/train-labels-idx1-ubyte.gz to ./data\MN
IST\raw\train-labels-idx1-ubyte.gz
  0%|          | 0/28881 [00:00<?, ?it/s]
Extracting ./data\MNIST\raw\train-labels-idx1-ubyte.gz to ./data\MNIST\raw

Downloading http://yann.lecun.com/exdb/mnist/t10k-images-idx3-ubyte.gz
Downloading http://yann.lecun.com/exdb/mnist/t10k-images-idx3-ubyte.gz to ./data\MNI
ST\raw\t10k-images-idx3-ubyte.gz
  0%|          | 0/1648877 [00:00<?, ?it/s]
```

```
Extracting ./data\MNIST\raw\t10k-images-idx3-ubyte.gz to ./data\MNIST\raw

Downloading http://yann.lecun.com/exdb/mnist/t10k-labels-idx1-ubyte.gz
Downloading http://yann.lecun.com/exdb/mnist/t10k-labels-idx1-ubyte.gz to ./data\MNI
ST\raw\t10k-labels-idx1-ubyte.gz
  0%|          | 0/4542 [00:00<?, ?it/s]
Extracting ./data\MNIST\raw\t10k-labels-idx1-ubyte.gz to ./data\MNIST\raw
```

数据加载

按照batch_size大小加载，并随机打乱

In [6]:
```python
data_loader = torch.utils.data.DataLoader(dataset=dataset,
                                          batch_size=batch_size,
                                          shuffle=True)
```

VAE模型类的定义

In [7]:
```python
# VAE模型
class VAE(nn.Module):
    def __init__(self, image_size=784, h_dim=400, z_dim=20):
        super(VAE, self).__init__()
        self.fc1 = nn.Linear(image_size, h_dim)
        self.fc2 = nn.Linear(h_dim, z_dim)
        self.fc3 = nn.Linear(h_dim, z_dim)
        self.fc4 = nn.Linear(z_dim, h_dim)
        self.fc5 = nn.Linear(h_dim, image_size)

    # 编码，学习高斯分布均值与方差
    def encode(self, x):
        h = F.relu(self.fc1(x))
        return self.fc2(h), self.fc3(h)

    # 将高斯分布均值与方差参数重表示，生成隐变量z   若x~N(mu, var*var)分布,则(x-mu)/v
    def reparameterize(self, mu, log_var):
        std = torch.exp(log_var / 2)
        eps = torch.randn_like(std)
        return mu + eps * std

    # 解码隐变量z
    def decode(self, z):
        h = F.relu(self.fc4(z))
        return F.sigmoid(self.fc5(h))

    # 计算重构值和隐变量z的分布参数
    def forward(self, x):
        mu, log_var = self.encode(x)   # 从原始样本x中学习隐变量z的分布，即学习服从高
        z = self.reparameterize(mu, log_var)   # 将高斯分布均值与方差参数重表示，生成
        x_reconst = self.decode(z)   # 解码隐变量z，生成重构x'
        return x_reconst, mu, log_var   # 返回重构值和隐变量的分布参数
```

构造VAE实例对象

In [8]:
```python
model = VAE().to(device)
print(model)
```

```
VAE(
  (fc1): Linear(in_features=784, out_features=400, bias=True)
  (fc2): Linear(in_features=400, out_features=20, bias=True)
  (fc3): Linear(in_features=400, out_features=20, bias=True)
  (fc4): Linear(in_features=20, out_features=400, bias=True)
  (fc5): Linear(in_features=400, out_features=784, bias=True)
)
```

选择优化器，并传入VAE模型参数和学习率

In [9]:
```python
optimizer = torch.optim.Adam(model.parameters(), lr=learning_rate)
```

开始训练

采用交叉熵损失

In [10]:
```python
# 开始训练一共15个循环
for epoch in range(num_epochs):
    for i, (x, _) in enumerate(data_loader):
        # 前向传播
        x = x.to(device).view(-1,image_size)  # 将batch_size*1*28*28 ---->batch_size
        x_reconst, mu, log_var = model(x)  # 将batch_size*748的x输入模型进行前向传播

        # 计算重构损失和KL散度
        # 重构损失
        reconst_loss = F.binary_cross_entropy(x_reconst, x, size_average=False)
        # KL散度
        kl_div = - 0.5 * torch.sum(1 + log_var - mu.pow(2) - log_var.exp())

        # 反向传播与优化
        # 计算误差(重构误差和KL散度值)
        loss = reconst_loss + kl_div
        # 清空上一步的残余更新参数值
        optimizer.zero_grad()
        # 误差反向传播，计算参数更新值
        loss.backward()
        # 将参数更新值施加到VAE model的parameters上
        optimizer.step()
        # 每迭代一定步骤，打印结果值
        if (i + 1) % 50 == 0:
            print("Epoch[{}/{}], Step [{}/{}], Reconst Loss(ce): {:.4f}, KL Div: {:.
                  .format(epoch + 1, num_epochs, i + 1, len(data_loader), reconst_lo

    with torch.no_grad():
        # 保存采样值
        # 生成随机数 z
        z = torch.randn(batch_size, z_dim).to(device)  # z的大小为batch_size * z_dim
        # 对随机数 z 进行解码decode输出
        out = model.decode(z).view(-1, 1, 28, 28)
        # 保存结果值
        save_image(out, os.path.join(sample_dir_ce, 'sampled-{}.png'.format(epoch +

        # 保存重构值
        # 将batch_size*748的x输入模型进行前向传播计算，获取重构值out
        out, _, _ = model(x)
        # 将输入与输出拼接在一起输出保存  batch_size*1*28*（28+28）=batch_size*1*28*
        x_concat = torch.cat([x.view(-1, 1, 28, 28), out.view(-1, 1, 28, 28)], dim=
        save_image(x_concat, os.path.join(sample_dir_ce, 'reconst-{}.png'.format(epo
```

```
F:\anaconda\lib\site-packages\torch\nn\functional.py:1944: UserWarning: nn.functiona
l.sigmoid is deprecated. Use torch.sigmoid instead.
  warnings.warn("nn.functional.sigmoid is deprecated. Use torch.sigmoid instead.")
F:\anaconda\lib\site-packages\torch\nn\_reduction.py:42: UserWarning: size_average a
nd reduce args will be deprecated, please use reduction='sum' instead.
  warnings.warn(warning.format(ret))
```

Epoch[1/15], Step [50/469], Reconst Loss(ce): 25841.7500, KL Div: 871.4764, Total Loss: 26713.2266
Epoch[1/15], Step [100/469], Reconst Loss(ce): 22817.9414, KL Div: 1279.1807, Total Loss: 24097.1211
Epoch[1/15], Step [150/469], Reconst Loss(ce): 19654.7539, KL Div: 1881.8120, Total Loss: 21536.5664
Epoch[1/15], Step [200/469], Reconst Loss(ce): 17491.5469, KL Div: 1983.8588, Total Loss: 19475.4062
Epoch[1/15], Step [250/469], Reconst Loss(ce): 15699.1064, KL Div: 2130.8135, Total Loss: 17829.9199
Epoch[1/15], Step [300/469], Reconst Loss(ce): 15941.3203, KL Div: 2224.9939, Total Loss: 18166.3145
Epoch[1/15], Step [350/469], Reconst Loss(ce): 14809.4883, KL Div: 2367.1362, Total Loss: 17176.6250
Epoch[1/15], Step [400/469], Reconst Loss(ce): 15230.5918, KL Div: 2485.4124, Total Loss: 17716.0039
Epoch[1/15], Step [450/469], Reconst Loss(ce): 14278.8789, KL Div: 2614.6392, Total Loss: 16893.5176
Epoch[2/15], Step [50/469], Reconst Loss(ce): 13349.8496, KL Div: 2741.2227, Total Loss: 16091.0723
Epoch[2/15], Step [100/469], Reconst Loss(ce): 13304.1641, KL Div: 2712.6096, Total Loss: 16016.7734
Epoch[2/15], Step [150/469], Reconst Loss(ce): 13107.3906, KL Div: 2772.2488, Total Loss: 15879.6396
Epoch[2/15], Step [200/469], Reconst Loss(ce): 12814.5674, KL Div: 2851.2637, Total Loss: 15665.8311
Epoch[2/15], Step [250/469], Reconst Loss(ce): 12602.6045, KL Div: 2823.8882, Total Loss: 15426.4922
Epoch[2/15], Step [300/469], Reconst Loss(ce): 12240.9111, KL Div: 2787.1011, Total Loss: 15028.0117
Epoch[2/15], Step [350/469], Reconst Loss(ce): 11783.7637, KL Div: 2930.8213, Total Loss: 14714.5850
Epoch[2/15], Step [400/469], Reconst Loss(ce): 11957.1211, KL Div: 2902.9758, Total Loss: 14860.0967
Epoch[2/15], Step [450/469], Reconst Loss(ce): 12217.8418, KL Div: 2914.8069, Total Loss: 15132.6484
Epoch[3/15], Step [50/469], Reconst Loss(ce): 12344.2012, KL Div: 3105.0898, Total Loss: 15449.2910
Epoch[3/15], Step [100/469], Reconst Loss(ce): 11910.2998, KL Div: 2916.6624, Total Loss: 14826.9619
Epoch[3/15], Step [150/469], Reconst Loss(ce): 11613.1074, KL Div: 3030.6223, Total Loss: 14643.7295
Epoch[3/15], Step [200/469], Reconst Loss(ce): 11906.0352, KL Div: 3129.4622, Total Loss: 15035.4971
Epoch[3/15], Step [250/469], Reconst Loss(ce): 11176.8164, KL Div: 3074.9114, Total Loss: 14251.7275
Epoch[3/15], Step [300/469], Reconst Loss(ce): 10949.6162, KL Div: 2983.6650, Total Loss: 13933.2812
Epoch[3/15], Step [350/469], Reconst Loss(ce): 11306.7285, KL Div: 3054.0452, Total Loss: 14360.7734
Epoch[3/15], Step [400/469], Reconst Loss(ce): 11616.0742, KL Div: 3146.1614, Total Loss: 14762.2354
Epoch[3/15], Step [450/469], Reconst Loss(ce): 11274.6016, KL Div: 3159.1533, Total Loss: 14433.7549
Epoch[4/15], Step [50/469], Reconst Loss(ce): 10932.7031, KL Div: 3145.1006, Total Loss: 14077.8037
Epoch[4/15], Step [100/469], Reconst Loss(ce): 11130.5098, KL Div: 3050.4011, Total Loss: 14180.9111
Epoch[4/15], Step [150/469], Reconst Loss(ce): 11119.0410, KL Div: 3029.8999, Total Loss: 14148.9414
Epoch[4/15], Step [200/469], Reconst Loss(ce): 11480.7285, KL Div: 3114.7864, Total Loss: 14595.5146
Epoch[4/15], Step [250/469], Reconst Loss(ce): 11557.8945, KL Div: 3127.8052, Total Loss: 14685.6992

Epoch[4/15], Step [300/469], Reconst Loss(ce): 11218.1475, KL Div: 3112.5708, Total Loss: 14330.7188
Epoch[4/15], Step [350/469], Reconst Loss(ce): 10573.1250, KL Div: 3125.0938, Total Loss: 13698.2188
Epoch[4/15], Step [400/469], Reconst Loss(ce): 11105.5801, KL Div: 3101.4380, Total Loss: 14207.0176
Epoch[4/15], Step [450/469], Reconst Loss(ce): 10437.7324, KL Div: 3072.6438, Total Loss: 13510.3760
Epoch[5/15], Step [50/469], Reconst Loss(ce): 10887.6416, KL Div: 3128.0364, Total Loss: 14015.6777
Epoch[5/15], Step [100/469], Reconst Loss(ce): 10906.2861, KL Div: 3030.9390, Total Loss: 13937.2246
Epoch[5/15], Step [150/469], Reconst Loss(ce): 10508.3652, KL Div: 3073.2793, Total Loss: 13581.6445
Epoch[5/15], Step [200/469], Reconst Loss(ce): 10570.6504, KL Div: 3066.3899, Total Loss: 13637.0400
Epoch[5/15], Step [250/469], Reconst Loss(ce): 10756.0371, KL Div: 3089.8550, Total Loss: 13845.8926
Epoch[5/15], Step [300/469], Reconst Loss(ce): 11274.4082, KL Div: 3170.4478, Total Loss: 14444.8555
Epoch[5/15], Step [350/469], Reconst Loss(ce): 11069.3125, KL Div: 3157.9575, Total Loss: 14227.2695
Epoch[5/15], Step [400/469], Reconst Loss(ce): 10904.5225, KL Div: 3097.8284, Total Loss: 14002.3506
Epoch[5/15], Step [450/469], Reconst Loss(ce): 10822.5996, KL Div: 3202.9294, Total Loss: 14025.5293
Epoch[6/15], Step [50/469], Reconst Loss(ce): 10707.8213, KL Div: 3040.0181, Total Loss: 13747.8398
Epoch[6/15], Step [100/469], Reconst Loss(ce): 10698.2920, KL Div: 3135.7935, Total Loss: 13834.0859
Epoch[6/15], Step [150/469], Reconst Loss(ce): 10968.2021, KL Div: 3232.3640, Total Loss: 14200.5664
Epoch[6/15], Step [200/469], Reconst Loss(ce): 11013.6406, KL Div: 3196.8889, Total Loss: 14210.5293
Epoch[6/15], Step [250/469], Reconst Loss(ce): 10981.2363, KL Div: 3109.6541, Total Loss: 14090.8906
Epoch[6/15], Step [300/469], Reconst Loss(ce): 10472.6650, KL Div: 3166.5623, Total Loss: 13639.2275
Epoch[6/15], Step [350/469], Reconst Loss(ce): 10601.2822, KL Div: 3095.5703, Total Loss: 13696.8525
Epoch[6/15], Step [400/469], Reconst Loss(ce): 10666.9131, KL Div: 3160.4663, Total Loss: 13827.3789
Epoch[6/15], Step [450/469], Reconst Loss(ce): 10719.1123, KL Div: 3107.0330, Total Loss: 13826.1455
Epoch[7/15], Step [50/469], Reconst Loss(ce): 10290.0576, KL Div: 3244.4839, Total Loss: 13534.5410
Epoch[7/15], Step [100/469], Reconst Loss(ce): 10683.4707, KL Div: 3214.5906, Total Loss: 13898.0615
Epoch[7/15], Step [150/469], Reconst Loss(ce): 10333.7871, KL Div: 3191.0361, Total Loss: 13524.8232
Epoch[7/15], Step [200/469], Reconst Loss(ce): 10676.5762, KL Div: 3158.5547, Total Loss: 13835.1309
Epoch[7/15], Step [250/469], Reconst Loss(ce): 10791.9766, KL Div: 3234.0457, Total Loss: 14026.0225
Epoch[7/15], Step [300/469], Reconst Loss(ce): 10406.6953, KL Div: 3111.6238, Total Loss: 13518.3193
Epoch[7/15], Step [350/469], Reconst Loss(ce): 10544.0918, KL Div: 3159.8071, Total Loss: 13703.8984
Epoch[7/15], Step [400/469], Reconst Loss(ce): 10233.0371, KL Div: 3165.5469, Total Loss: 13398.5840
Epoch[7/15], Step [450/469], Reconst Loss(ce): 10757.8320, KL Div: 3170.4932, Total Loss: 13928.3252
Epoch[8/15], Step [50/469], Reconst Loss(ce): 10582.1113, KL Div: 3229.8201, Total Loss: 13811.9316

Epoch[8/15], Step [100/469], Reconst Loss(ce): 10619.9219, KL Div: 3250.1130, Total Loss: 13870.0352
Epoch[8/15], Step [150/469], Reconst Loss(ce): 10641.2266, KL Div: 3241.5056, Total Loss: 13882.7324
Epoch[8/15], Step [200/469], Reconst Loss(ce): 10512.8340, KL Div: 3172.1619, Total Loss: 13684.9961
Epoch[8/15], Step [250/469], Reconst Loss(ce): 10423.5488, KL Div: 3229.1279, Total Loss: 13652.6768
Epoch[8/15], Step [300/469], Reconst Loss(ce): 10482.2988, KL Div: 3273.6521, Total Loss: 13755.9512
Epoch[8/15], Step [350/469], Reconst Loss(ce): 10141.5078, KL Div: 3074.2007, Total Loss: 13215.7090
Epoch[8/15], Step [400/469], Reconst Loss(ce): 10707.0039, KL Div: 3264.0930, Total Loss: 13971.0967
Epoch[8/15], Step [450/469], Reconst Loss(ce): 10566.0889, KL Div: 3160.1177, Total Loss: 13726.2070
Epoch[9/15], Step [50/469], Reconst Loss(ce): 10782.7402, KL Div: 3227.9927, Total Loss: 14010.7324
Epoch[9/15], Step [100/469], Reconst Loss(ce): 10167.1709, KL Div: 3135.1401, Total Loss: 13302.3105
Epoch[9/15], Step [150/469], Reconst Loss(ce): 10323.9902, KL Div: 3163.1064, Total Loss: 13487.0967
Epoch[9/15], Step [200/469], Reconst Loss(ce): 9763.1143, KL Div: 3162.4255, Total Loss: 12925.5400
Epoch[9/15], Step [250/469], Reconst Loss(ce): 9951.7422, KL Div: 3126.4863, Total Loss: 13078.2285
Epoch[9/15], Step [300/469], Reconst Loss(ce): 10774.8291, KL Div: 3166.5146, Total Loss: 13941.3438
Epoch[9/15], Step [350/469], Reconst Loss(ce): 10953.1406, KL Div: 3285.9629, Total Loss: 14239.1035
Epoch[9/15], Step [400/469], Reconst Loss(ce): 10513.0801, KL Div: 3206.2305, Total Loss: 13719.3105
Epoch[9/15], Step [450/469], Reconst Loss(ce): 10430.9873, KL Div: 3243.7810, Total Loss: 13674.7686
Epoch[10/15], Step [50/469], Reconst Loss(ce): 10902.3574, KL Div: 3264.2834, Total Loss: 14166.6406
Epoch[10/15], Step [100/469], Reconst Loss(ce): 10142.8701, KL Div: 3178.8608, Total Loss: 13321.7305
Epoch[10/15], Step [150/469], Reconst Loss(ce): 10204.4961, KL Div: 3228.6414, Total Loss: 13433.1377
Epoch[10/15], Step [200/469], Reconst Loss(ce): 10313.6006, KL Div: 3200.1646, Total Loss: 13513.7656
Epoch[10/15], Step [250/469], Reconst Loss(ce): 10166.5781, KL Div: 3108.9756, Total Loss: 13275.5537
Epoch[10/15], Step [300/469], Reconst Loss(ce): 10238.0000, KL Div: 3095.9600, Total Loss: 13333.9600
Epoch[10/15], Step [350/469], Reconst Loss(ce): 10510.5596, KL Div: 3270.3765, Total Loss: 13780.9355
Epoch[10/15], Step [400/469], Reconst Loss(ce): 10421.1455, KL Div: 3306.0872, Total Loss: 13727.2324
Epoch[10/15], Step [450/469], Reconst Loss(ce): 10249.2480, KL Div: 3147.4158, Total Loss: 13396.6641
Epoch[11/15], Step [50/469], Reconst Loss(ce): 10489.3555, KL Div: 3221.2964, Total Loss: 13710.6523
Epoch[11/15], Step [100/469], Reconst Loss(ce): 10617.3369, KL Div: 3353.9023, Total Loss: 13971.2393
Epoch[11/15], Step [150/469], Reconst Loss(ce): 10530.0537, KL Div: 3284.2529, Total Loss: 13814.3066
Epoch[11/15], Step [200/469], Reconst Loss(ce): 10321.5430, KL Div: 3239.1592, Total Loss: 13560.7021
Epoch[11/15], Step [250/469], Reconst Loss(ce): 10574.2559, KL Div: 3260.9634, Total Loss: 13835.2188
Epoch[11/15], Step [300/469], Reconst Loss(ce): 10708.5840, KL Div: 3265.9558, Total Loss: 13974.5400

Epoch[11/15], Step [350/469], Reconst Loss(ce): 10359.6377, KL Div: 3244.2437, Total Loss: 13603.8809
Epoch[11/15], Step [400/469], Reconst Loss(ce): 10161.8184, KL Div: 3350.8362, Total Loss: 13512.6543
Epoch[11/15], Step [450/469], Reconst Loss(ce): 10543.7627, KL Div: 3239.2747, Total Loss: 13783.0371
Epoch[12/15], Step [50/469], Reconst Loss(ce): 9881.4482, KL Div: 3185.2913, Total Loss: 13066.7393
Epoch[12/15], Step [100/469], Reconst Loss(ce): 10146.7930, KL Div: 3289.1631, Total Loss: 13435.9561
Epoch[12/15], Step [150/469], Reconst Loss(ce): 9988.7598, KL Div: 3243.0574, Total Loss: 13231.8174
Epoch[12/15], Step [200/469], Reconst Loss(ce): 10754.9580, KL Div: 3353.8354, Total Loss: 14108.7930
Epoch[12/15], Step [250/469], Reconst Loss(ce): 10055.7227, KL Div: 3273.2644, Total Loss: 13328.9873
Epoch[12/15], Step [300/469], Reconst Loss(ce): 10279.4590, KL Div: 3176.7781, Total Loss: 13456.2373
Epoch[12/15], Step [350/469], Reconst Loss(ce): 10022.4961, KL Div: 3172.8335, Total Loss: 13195.3301
Epoch[12/15], Step [400/469], Reconst Loss(ce): 10079.0557, KL Div: 3235.4712, Total Loss: 13314.5273
Epoch[12/15], Step [450/469], Reconst Loss(ce): 10308.7012, KL Div: 3244.9604, Total Loss: 13553.6621
Epoch[13/15], Step [50/469], Reconst Loss(ce): 10389.6523, KL Div: 3350.9390, Total Loss: 13740.5918
Epoch[13/15], Step [100/469], Reconst Loss(ce): 10264.7949, KL Div: 3254.9941, Total Loss: 13519.7891
Epoch[13/15], Step [150/469], Reconst Loss(ce): 9978.0654, KL Div: 3148.5591, Total Loss: 13126.6250
Epoch[13/15], Step [200/469], Reconst Loss(ce): 10575.4014, KL Div: 3231.6318, Total Loss: 13807.0332
Epoch[13/15], Step [250/469], Reconst Loss(ce): 10134.8926, KL Div: 3206.0029, Total Loss: 13340.8955
Epoch[13/15], Step [300/469], Reconst Loss(ce): 10234.7441, KL Div: 3143.6501, Total Loss: 13378.3945
Epoch[13/15], Step [350/469], Reconst Loss(ce): 10573.4004, KL Div: 3337.7810, Total Loss: 13911.1816
Epoch[13/15], Step [400/469], Reconst Loss(ce): 10255.0596, KL Div: 3297.7002, Total Loss: 13552.7598
Epoch[13/15], Step [450/469], Reconst Loss(ce): 10493.9336, KL Div: 3280.8960, Total Loss: 13774.8301
Epoch[14/15], Step [50/469], Reconst Loss(ce): 9953.2520, KL Div: 3082.4363, Total Loss: 13035.6885
Epoch[14/15], Step [100/469], Reconst Loss(ce): 10369.0938, KL Div: 3259.0886, Total Loss: 13628.1826
Epoch[14/15], Step [150/469], Reconst Loss(ce): 10147.6572, KL Div: 3291.6099, Total Loss: 13439.2676
Epoch[14/15], Step [200/469], Reconst Loss(ce): 10335.7793, KL Div: 3246.7800, Total Loss: 13582.5596
Epoch[14/15], Step [250/469], Reconst Loss(ce): 10356.6914, KL Div: 3190.0190, Total Loss: 13546.7109
Epoch[14/15], Step [300/469], Reconst Loss(ce): 10487.6680, KL Div: 3227.4180, Total Loss: 13715.0859
Epoch[14/15], Step [350/469], Reconst Loss(ce): 10923.1436, KL Div: 3300.6731, Total Loss: 14223.8164
Epoch[14/15], Step [400/469], Reconst Loss(ce): 10154.9033, KL Div: 3158.9399, Total Loss: 13313.8438
Epoch[14/15], Step [450/469], Reconst Loss(ce): 10777.1084, KL Div: 3291.0137, Total Loss: 14068.1221
Epoch[15/15], Step [50/469], Reconst Loss(ce): 9945.8730, KL Div: 3133.8223, Total Loss: 13079.6953
Epoch[15/15], Step [100/469], Reconst Loss(ce): 9974.9609, KL Div: 3266.8635, Total Loss: 13241.8242

```
Epoch[15/15], Step [150/469], Reconst Loss(ce): 10167.6592, KL Div: 3284.5654, Total
Loss: 13452.2246
Epoch[15/15], Step [200/469], Reconst Loss(ce): 10069.2578, KL Div: 3178.0007, Total
Loss: 13247.2588
Epoch[15/15], Step [250/469], Reconst Loss(ce): 10222.6387, KL Div: 3396.8940, Total
Loss: 13619.5332
Epoch[15/15], Step [300/469], Reconst Loss(ce): 9915.0625, KL Div: 3195.4790, Total
Loss: 13110.5410
Epoch[15/15], Step [350/469], Reconst Loss(ce): 10041.9287, KL Div: 3250.9956, Total
Loss: 13292.9238
Epoch[15/15], Step [400/469], Reconst Loss(ce): 10043.3262, KL Div: 3239.6885, Total
Loss: 13283.0146
Epoch[15/15], Step [450/469], Reconst Loss(ce): 9973.1025, KL Div: 3097.5566, Total
Loss: 13070.6592
```

采用L2损失（MSE）

In [11]:
```python
# 构造VAE实例对象
model = VAE().to(device)

# 选择优化器，并传入VAE模型参数和学习率
optimizer = torch.optim.Adam(model.parameters(), lr=learning_rate)
# 开始训练一共15个循环
for epoch in range(num_epochs):
    for i, (x, _) in enumerate(data_loader):
        # 前向传播
        x = x.to(device).view(-1,image_size)  # 将batch_size*1*28*28 ---->batch_size
        x_reconst, mu, log_var = model(x)  # 将batch_size*748的x输入模型进行前向传播

        # 计算重构损失和KL散度
        # 重构损失
        reconst_loss = F.mse_loss(x_reconst, x, size_average=False)
        # KL散度
        kl_div = - 0.5 * torch.sum(1 + log_var - mu.pow(2) - log_var.exp())

        # 反向传播与优化
        # 计算误差(重构误差和KL散度值)
        loss = reconst_loss + kl_div
        # 清空上一步的残余更新参数值
        optimizer.zero_grad()
        # 误差反向传播，计算参数更新值
        loss.backward()
        # 将参数更新值施加到VAE model的parameters上
        optimizer.step()
        # 每迭代一定步骤，打印结果值
        if (i + 1) % 50 == 0:
            print("Epoch[{}/{}], Step [{}/{}], Reconst Loss(mse): {:.4f}, KL Div: {:
                  .format(epoch + 1, num_epochs, i + 1, len(data_loader), reconst_lo

    with torch.no_grad():
        # 保存采样值
        # 生成随机数 z
        z = torch.randn(batch_size, z_dim).to(device)  # z的大小为batch_size * z_dim
        # 对随机数 z 进行解码decode输出
        out = model.decode(z).view(-1, 1, 28, 28)
        # 保存结果值
        save_image(out, os.path.join(sample_dir_mse, 'sampled-{}.png'.format(epoch +

        # 保存重构值
        # 将batch_size*748的x输入模型进行前向传播计算，获取重构值out
        out, _, _ = model(x)
        # 将输入与输出拼接在一起输出保存  batch_size*1*28*（28+28）=batch_size*1*28*
```

```python
        x_concat = torch.cat([x.view(-1, 1, 28, 28), out.view(-1, 1, 28, 28)], dim=
        save_image(x_concat, os.path.join(sample_dir_mse, 'reconst-{}.png'.format(ep
```

```python
        x_concat = torch.cat([x.view(-1, 1, 28, 28), out.view(-1, 1, 28, 28)], dim=
        save_image(x_concat, os.path.join(sample_dir_mse, 'reconst-{}.png'.format(ep
```

Epoch[1/15], Step [50/469], Reconst Loss(mse): 6973.7300, KL Div: 154.3004, Total Loss: 7128.0303
Epoch[1/15], Step [100/469], Reconst Loss(mse): 6396.5352, KL Div: 361.9924, Total Loss: 6758.5273
Epoch[1/15], Step [150/469], Reconst Loss(mse): 5510.8750, KL Div: 610.3787, Total Loss: 6121.2539
Epoch[1/15], Step [200/469], Reconst Loss(mse): 4777.3623, KL Div: 791.0031, Total Loss: 5568.3652
Epoch[1/15], Step [250/469], Reconst Loss(mse): 4434.1787, KL Div: 932.3185, Total Loss: 5366.4971
Epoch[1/15], Step [300/469], Reconst Loss(mse): 4133.1909, KL Div: 1002.0323, Total Loss: 5135.2231
Epoch[1/15], Step [350/469], Reconst Loss(mse): 3866.7673, KL Div: 1082.1986, Total Loss: 4948.9658
Epoch[1/15], Step [400/469], Reconst Loss(mse): 3775.3081, KL Div: 1095.6543, Total Loss: 4870.9624
Epoch[1/15], Step [450/469], Reconst Loss(mse): 3451.5962, KL Div: 1175.2139, Total Loss: 4626.8101
Epoch[2/15], Step [50/469], Reconst Loss(mse): 3319.1658, KL Div: 1152.6489, Total Loss: 4471.8145
Epoch[2/15], Step [100/469], Reconst Loss(mse): 3347.5181, KL Div: 1249.6021, Total Loss: 4597.1201
Epoch[2/15], Step [150/469], Reconst Loss(mse): 3363.7097, KL Div: 1214.2185, Total Loss: 4577.9282
Epoch[2/15], Step [200/469], Reconst Loss(mse): 2990.5923, KL Div: 1246.6508, Total Loss: 4237.2432
Epoch[2/15], Step [250/469], Reconst Loss(mse): 3044.0264, KL Div: 1365.9919, Total Loss: 4410.0186
Epoch[2/15], Step [300/469], Reconst Loss(mse): 3148.2422, KL Div: 1260.1238, Total Loss: 4408.3662
Epoch[2/15], Step [350/469], Reconst Loss(mse): 2790.9072, KL Div: 1377.3000, Total Loss: 4168.2070
Epoch[2/15], Step [400/469], Reconst Loss(mse): 3167.7598, KL Div: 1409.4130, Total Loss: 4577.1729
Epoch[2/15], Step [450/469], Reconst Loss(mse): 3102.7263, KL Div: 1349.0823, Total Loss: 4451.8086
Epoch[3/15], Step [50/469], Reconst Loss(mse): 2992.7209, KL Div: 1337.0776, Total Loss: 4329.7988
Epoch[3/15], Step [100/469], Reconst Loss(mse): 2854.2007, KL Div: 1380.5740, Total Loss: 4234.7744
Epoch[3/15], Step [150/469], Reconst Loss(mse): 2811.6069, KL Div: 1377.9650, Total Loss: 4189.5718
Epoch[3/15], Step [200/469], Reconst Loss(mse): 2892.4067, KL Div: 1323.3977, Total Loss: 4215.8047
Epoch[3/15], Step [250/469], Reconst Loss(mse): 2829.7874, KL Div: 1386.9231, Total Loss: 4216.7104
Epoch[3/15], Step [300/469], Reconst Loss(mse): 2710.9175, KL Div: 1431.7325, Total Loss: 4142.6499
Epoch[3/15], Step [350/469], Reconst Loss(mse): 2751.0579, KL Div: 1466.7628, Total Loss: 4217.8208
Epoch[3/15], Step [400/469], Reconst Loss(mse): 2744.5762, KL Div: 1458.6315, Total Loss: 4203.2075
Epoch[3/15], Step [450/469], Reconst Loss(mse): 2709.9490, KL Div: 1468.3157, Total Loss: 4178.2646
Epoch[4/15], Step [50/469], Reconst Loss(mse): 2657.1104, KL Div: 1474.7085, Total Loss: 4131.8188
Epoch[4/15], Step [100/469], Reconst Loss(mse): 2560.9961, KL Div: 1389.4248, Total Loss: 3950.4209
Epoch[4/15], Step [150/469], Reconst Loss(mse): 2752.1213, KL Div: 1488.0103, Total Loss: 4240.1318
Epoch[4/15], Step [200/469], Reconst Loss(mse): 2656.9221, KL Div: 1463.2528, Total Loss: 4120.1748
Epoch[4/15], Step [250/469], Reconst Loss(mse): 2693.9175, KL Div: 1428.1210, Total Loss: 4122.0386

Epoch[4/15], Step [300/469], Reconst Loss(mse): 2835.5811, KL Div: 1477.5924, Total Loss: 4313.1733
Epoch[4/15], Step [350/469], Reconst Loss(mse): 2664.7161, KL Div: 1449.9780, Total Loss: 4114.6943
Epoch[4/15], Step [400/469], Reconst Loss(mse): 2489.1213, KL Div: 1442.5236, Total Loss: 3931.6450
Epoch[4/15], Step [450/469], Reconst Loss(mse): 2667.9558, KL Div: 1414.8674, Total Loss: 4082.8232
Epoch[5/15], Step [50/469], Reconst Loss(mse): 2736.4382, KL Div: 1420.2408, Total Loss: 4156.6792
Epoch[5/15], Step [100/469], Reconst Loss(mse): 2525.4048, KL Div: 1523.6017, Total Loss: 4049.0063
Epoch[5/15], Step [150/469], Reconst Loss(mse): 2541.6013, KL Div: 1447.4602, Total Loss: 3989.0615
Epoch[5/15], Step [200/469], Reconst Loss(mse): 2682.8254, KL Div: 1467.4485, Total Loss: 4150.2739
Epoch[5/15], Step [250/469], Reconst Loss(mse): 2635.2754, KL Div: 1461.6112, Total Loss: 4096.8867
Epoch[5/15], Step [300/469], Reconst Loss(mse): 2612.2314, KL Div: 1482.7844, Total Loss: 4095.0159
Epoch[5/15], Step [350/469], Reconst Loss(mse): 2407.2412, KL Div: 1570.2694, Total Loss: 3977.5107
Epoch[5/15], Step [400/469], Reconst Loss(mse): 2833.5278, KL Div: 1515.4331, Total Loss: 4348.9609
Epoch[5/15], Step [450/469], Reconst Loss(mse): 2558.6116, KL Div: 1523.7968, Total Loss: 4082.4082
Epoch[6/15], Step [50/469], Reconst Loss(mse): 2550.3701, KL Div: 1512.2664, Total Loss: 4062.6365
Epoch[6/15], Step [100/469], Reconst Loss(mse): 2437.7693, KL Div: 1471.2820, Total Loss: 3909.0513
Epoch[6/15], Step [150/469], Reconst Loss(mse): 2357.6787, KL Div: 1531.2489, Total Loss: 3888.9277
Epoch[6/15], Step [200/469], Reconst Loss(mse): 2366.5242, KL Div: 1456.2410, Total Loss: 3822.7651
Epoch[6/15], Step [250/469], Reconst Loss(mse): 2537.5859, KL Div: 1469.9149, Total Loss: 4007.5010
Epoch[6/15], Step [300/469], Reconst Loss(mse): 2356.1902, KL Div: 1519.1003, Total Loss: 3875.2905
Epoch[6/15], Step [350/469], Reconst Loss(mse): 2477.7622, KL Div: 1523.2212, Total Loss: 4000.9834
Epoch[6/15], Step [400/469], Reconst Loss(mse): 2461.7024, KL Div: 1545.8147, Total Loss: 4007.5171
Epoch[6/15], Step [450/469], Reconst Loss(mse): 2487.5669, KL Div: 1559.3236, Total Loss: 4046.8906
Epoch[7/15], Step [50/469], Reconst Loss(mse): 2497.7581, KL Div: 1564.6125, Total Loss: 4062.3706
Epoch[7/15], Step [100/469], Reconst Loss(mse): 2351.0498, KL Div: 1569.0259, Total Loss: 3920.0757
Epoch[7/15], Step [150/469], Reconst Loss(mse): 2251.6855, KL Div: 1605.6532, Total Loss: 3857.3389
Epoch[7/15], Step [200/469], Reconst Loss(mse): 2513.3906, KL Div: 1440.6034, Total Loss: 3953.9941
Epoch[7/15], Step [250/469], Reconst Loss(mse): 2504.2788, KL Div: 1448.1201, Total Loss: 3952.3989
Epoch[7/15], Step [300/469], Reconst Loss(mse): 2349.9360, KL Div: 1478.1252, Total Loss: 3828.0613
Epoch[7/15], Step [350/469], Reconst Loss(mse): 2293.0010, KL Div: 1537.2242, Total Loss: 3830.2251
Epoch[7/15], Step [400/469], Reconst Loss(mse): 2432.5327, KL Div: 1495.8718, Total Loss: 3928.4045
Epoch[7/15], Step [450/469], Reconst Loss(mse): 2415.8545, KL Div: 1598.4114, Total Loss: 4014.2659
Epoch[8/15], Step [50/469], Reconst Loss(mse): 2329.5483, KL Div: 1602.9633, Total Loss: 3932.5117

Epoch[8/15], Step [100/469], Reconst Loss(mse): 2261.7456, KL Div: 1551.5867, Total Loss: 3813.3323
Epoch[8/15], Step [150/469], Reconst Loss(mse): 2565.9932, KL Div: 1591.5781, Total Loss: 4157.5713
Epoch[8/15], Step [200/469], Reconst Loss(mse): 2449.1523, KL Div: 1456.9005, Total Loss: 3906.0527
Epoch[8/15], Step [250/469], Reconst Loss(mse): 2426.6667, KL Div: 1484.1361, Total Loss: 3910.8027
Epoch[8/15], Step [300/469], Reconst Loss(mse): 2415.1975, KL Div: 1568.3170, Total Loss: 3983.5146
Epoch[8/15], Step [350/469], Reconst Loss(mse): 2362.1909, KL Div: 1534.2085, Total Loss: 3896.3994
Epoch[8/15], Step [400/469], Reconst Loss(mse): 2538.3857, KL Div: 1550.3107, Total Loss: 4088.6963
Epoch[8/15], Step [450/469], Reconst Loss(mse): 2379.3848, KL Div: 1531.9885, Total Loss: 3911.3733
Epoch[9/15], Step [50/469], Reconst Loss(mse): 2506.0190, KL Div: 1542.4110, Total Loss: 4048.4302
Epoch[9/15], Step [100/469], Reconst Loss(mse): 2297.5068, KL Div: 1593.4532, Total Loss: 3890.9600
Epoch[9/15], Step [150/469], Reconst Loss(mse): 2454.5952, KL Div: 1536.9386, Total Loss: 3991.5337
Epoch[9/15], Step [200/469], Reconst Loss(mse): 2306.0698, KL Div: 1532.7726, Total Loss: 3838.8423
Epoch[9/15], Step [250/469], Reconst Loss(mse): 2359.2502, KL Div: 1532.3701, Total Loss: 3891.6204
Epoch[9/15], Step [300/469], Reconst Loss(mse): 2381.2617, KL Div: 1528.9604, Total Loss: 3910.2222
Epoch[9/15], Step [350/469], Reconst Loss(mse): 2361.5425, KL Div: 1590.1993, Total Loss: 3951.7417
Epoch[9/15], Step [400/469], Reconst Loss(mse): 2474.4736, KL Div: 1568.5100, Total Loss: 4042.9836
Epoch[9/15], Step [450/469], Reconst Loss(mse): 2588.9993, KL Div: 1584.8027, Total Loss: 4173.8018
Epoch[10/15], Step [50/469], Reconst Loss(mse): 2350.3257, KL Div: 1557.2728, Total Loss: 3907.5986
Epoch[10/15], Step [100/469], Reconst Loss(mse): 2337.9011, KL Div: 1548.0048, Total Loss: 3885.9058
Epoch[10/15], Step [150/469], Reconst Loss(mse): 2429.8745, KL Div: 1545.8638, Total Loss: 3975.7383
Epoch[10/15], Step [200/469], Reconst Loss(mse): 2267.0718, KL Div: 1623.0623, Total Loss: 3890.1340
Epoch[10/15], Step [250/469], Reconst Loss(mse): 2394.9685, KL Div: 1533.0208, Total Loss: 3927.9893
Epoch[10/15], Step [300/469], Reconst Loss(mse): 2372.3999, KL Div: 1555.6188, Total Loss: 3928.0186
Epoch[10/15], Step [350/469], Reconst Loss(mse): 2360.9639, KL Div: 1587.8489, Total Loss: 3948.8127
Epoch[10/15], Step [400/469], Reconst Loss(mse): 2141.9563, KL Div: 1547.6787, Total Loss: 3689.6350
Epoch[10/15], Step [450/469], Reconst Loss(mse): 2371.5117, KL Div: 1561.4539, Total Loss: 3932.9656
Epoch[11/15], Step [50/469], Reconst Loss(mse): 2310.3877, KL Div: 1591.0576, Total Loss: 3901.4453
Epoch[11/15], Step [100/469], Reconst Loss(mse): 2255.4771, KL Div: 1592.6659, Total Loss: 3848.1431
Epoch[11/15], Step [150/469], Reconst Loss(mse): 2399.6265, KL Div: 1553.7008, Total Loss: 3953.3271
Epoch[11/15], Step [200/469], Reconst Loss(mse): 2223.6470, KL Div: 1604.9319, Total Loss: 3828.5789
Epoch[11/15], Step [250/469], Reconst Loss(mse): 2282.9033, KL Div: 1593.5903, Total Loss: 3876.4937
Epoch[11/15], Step [300/469], Reconst Loss(mse): 2525.0454, KL Div: 1657.5061, Total Loss: 4182.5518

Epoch[11/15], Step [350/469], Reconst Loss(mse): 2263.9443, KL Div: 1586.3430, Total Loss: 3850.2874
Epoch[11/15], Step [400/469], Reconst Loss(mse): 2413.9570, KL Div: 1574.2083, Total Loss: 3988.1653
Epoch[11/15], Step [450/469], Reconst Loss(mse): 2284.5083, KL Div: 1551.2960, Total Loss: 3835.8042
Epoch[12/15], Step [50/469], Reconst Loss(mse): 2362.5637, KL Div: 1597.0570, Total Loss: 3959.6206
Epoch[12/15], Step [100/469], Reconst Loss(mse): 2249.6401, KL Div: 1571.9744, Total Loss: 3821.6145
Epoch[12/15], Step [150/469], Reconst Loss(mse): 2385.1206, KL Div: 1534.6921, Total Loss: 3919.8127
Epoch[12/15], Step [200/469], Reconst Loss(mse): 2266.9326, KL Div: 1595.9904, Total Loss: 3862.9229
Epoch[12/15], Step [250/469], Reconst Loss(mse): 2426.6958, KL Div: 1605.5536, Total Loss: 4032.2495
Epoch[12/15], Step [300/469], Reconst Loss(mse): 2266.2505, KL Div: 1557.5164, Total Loss: 3823.7668
Epoch[12/15], Step [350/469], Reconst Loss(mse): 2140.7812, KL Div: 1633.8693, Total Loss: 3774.6504
Epoch[12/15], Step [400/469], Reconst Loss(mse): 2344.3208, KL Div: 1534.3337, Total Loss: 3878.6545
Epoch[12/15], Step [450/469], Reconst Loss(mse): 2285.1714, KL Div: 1555.1713, Total Loss: 3840.3428
Epoch[13/15], Step [50/469], Reconst Loss(mse): 2323.0181, KL Div: 1484.0713, Total Loss: 3807.0894
Epoch[13/15], Step [100/469], Reconst Loss(mse): 2307.2844, KL Div: 1537.6405, Total Loss: 3844.9248
Epoch[13/15], Step [150/469], Reconst Loss(mse): 2337.8855, KL Div: 1558.3075, Total Loss: 3896.1929
Epoch[13/15], Step [200/469], Reconst Loss(mse): 2272.4119, KL Div: 1512.2064, Total Loss: 3784.6182
Epoch[13/15], Step [250/469], Reconst Loss(mse): 2386.1643, KL Div: 1621.9792, Total Loss: 4008.1436
Epoch[13/15], Step [300/469], Reconst Loss(mse): 2148.4888, KL Div: 1585.7637, Total Loss: 3734.2524
Epoch[13/15], Step [350/469], Reconst Loss(mse): 2292.0774, KL Div: 1622.7734, Total Loss: 3914.8508
Epoch[13/15], Step [400/469], Reconst Loss(mse): 2274.1548, KL Div: 1562.2068, Total Loss: 3836.3616
Epoch[13/15], Step [450/469], Reconst Loss(mse): 2362.9590, KL Div: 1617.2053, Total Loss: 3980.1643
Epoch[14/15], Step [50/469], Reconst Loss(mse): 2376.6042, KL Div: 1570.7305, Total Loss: 3947.3347
Epoch[14/15], Step [100/469], Reconst Loss(mse): 2344.6340, KL Div: 1552.7546, Total Loss: 3897.3887
Epoch[14/15], Step [150/469], Reconst Loss(mse): 2222.7510, KL Div: 1516.0693, Total Loss: 3738.8203
Epoch[14/15], Step [200/469], Reconst Loss(mse): 2287.7336, KL Div: 1557.6497, Total Loss: 3845.3833
Epoch[14/15], Step [250/469], Reconst Loss(mse): 2278.4243, KL Div: 1585.7559, Total Loss: 3864.1802
Epoch[14/15], Step [300/469], Reconst Loss(mse): 2435.1375, KL Div: 1576.8744, Total Loss: 4012.0117
Epoch[14/15], Step [350/469], Reconst Loss(mse): 2302.5396, KL Div: 1587.2461, Total Loss: 3889.7856
Epoch[14/15], Step [400/469], Reconst Loss(mse): 2393.8250, KL Div: 1585.1714, Total Loss: 3978.9963
Epoch[14/15], Step [450/469], Reconst Loss(mse): 2355.9204, KL Div: 1545.6503, Total Loss: 3901.5708
Epoch[15/15], Step [50/469], Reconst Loss(mse): 2216.5369, KL Div: 1587.6764, Total Loss: 3804.2134
Epoch[15/15], Step [100/469], Reconst Loss(mse): 2238.8789, KL Div: 1578.5223, Total Loss: 3817.4014

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Epoch[15/15], Step [150/469], Reconst Loss(mse): 2163.4841, KL Div: 1613.1589, Total
Loss: 3776.6431
Epoch[15/15], Step [200/469], Reconst Loss(mse): 2161.3843, KL Div: 1577.4924, Total
Loss: 3738.8767
Epoch[15/15], Step [250/469], Reconst Loss(mse): 2319.4080, KL Div: 1572.9272, Total
Loss: 3892.3352
Epoch[15/15], Step [300/469], Reconst Loss(mse): 2265.9373, KL Div: 1569.1394, Total
Loss: 3835.0767
Epoch[15/15], Step [350/469], Reconst Loss(mse): 2163.9868, KL Div: 1550.8623, Total
Loss: 3714.8491
Epoch[15/15], Step [400/469], Reconst Loss(mse): 2133.6877, KL Div: 1561.0519, Total
Loss: 3694.7397
Epoch[15/15], Step [450/469], Reconst Loss(mse): 2300.3076, KL Div: 1614.0750, Total
Loss: 3914.3826
```

中级要求

目标：　最大化似然函数 $\log(p(x))$，即 $\ln(p(x))$

∵ $p(x,z) = p(x)\,p(z|x)$ (1)

∴ $p(x) = \dfrac{p(x,z)}{p(z|x)}$ (2)

∴ $\ln p(x) = \ln p(x,z) - \ln p(z|x)$ (3)

设 $q(z)$ 为任一分布，则：

$$\ln p(x) = \ln \frac{p(x,z)}{q(z)} - \ln \frac{p(z|x)}{q(z)}$$ (4)

对 (4) 两端求期望：

$$E_{q(z)}[\ln p(x)] = E_{q(z)}\left[\ln \frac{p(x,z)}{q(z)}\right] - E_{q(z)}\left[\ln \frac{p(z|x)}{q(z)}\right]$$ (5)

展开，有：

$$\int_z q(z)\ln p(x)\,dz = \int_z q(z)\ln \frac{p(x,z)}{q(z)}\,dz - \int_z q(z)\ln \frac{p(z|x)}{q(z)}\,dz$$ (6)

∵ $D_{KL} = KL\left(q(z|x) \| p(z|x)\right) = \int q(z|x)\ln \frac{q(z|x)}{p(z|x)}\,dz$

∴ $E_{q(z)}[\ln p(x)] = E_{q(z)}\left[\ln \frac{p(x,z)}{q(z)}\right] + KL\left(q(z) \| p(z|x)\right)$ (7)

∴ 令 $ELBO = E_{q(z)}\left[\ln \frac{p(x,z)}{q(z)}\right]$，且由定义，$D_{KL} \geq 0$

∴ $E_{q(z)}[\ln p(x)] = ELBO + KL\left(q(z) \| p(z|x)\right)$ (8)

∴ 当且仅当 $q(z) = q(z|x)$ 时，$E_{q(z)}[\ln p(x)] = ELBO$

∵ 在 VAE 中，常用 $q(z|x)$ 近似 $p(z|x)$

∴ 此时 $E_{q(z)}[\ln p(x)] = ELBO$

故只须最大化 ELBO 即可

由 (8)：$ELBO = E_{q(z)}[\ln p(x|z)] - KL\left(q(z) \| p(z)\right)$ (9)

∵ 对于 $q(z)$，x 与 z 独立，故为了让 encoder $q(z|x)$ 接近，将 $p(z)$ 改为 $q(z|x)$

∴ $ELBO = E_{q(z|x)}[\ln p(x|z)] - KL\left(q(z|x) \| p(z)\right)$ (10)

目标：最大化似然函数 $\log(p(x))$，即 $\ln(p(x))$

$\because \quad p(x,z) = p(x)\, p(z|x) \quad (1)$

$\therefore \quad p(x) = \dfrac{p(x,z)}{p(z|x)} \quad (2)$

$\therefore \quad \ln p(x) = \ln p(x,z) - \ln p(z|x) \quad (3)$

设 $q(z)$ 为任一分布，则：

$$\ln p(x) = \ln \frac{p(x,z)}{q(z)} - \ln \frac{p(z|x)}{q(z)} \quad (4)$$

对 (4) 两端求期望：

$$E_{q(z)}\big[\ln p(x)\big] = E_{q(z)}\Big[\ln \frac{p(x,z)}{q(z)}\Big] - E_{q(z)}\Big[\ln \frac{p(z|x)}{q(z)}\Big] \quad (5)$$

展开，有：

$$\int_z q(z)\ln p(x)\, dz = \int_z q(z)\ln \frac{p(x,z)}{q(z)}\, dz - \int_z q(z)\ln \frac{p(z|x)}{q(z)}\, dz \quad (6)$$

$\therefore \quad D_{KL} = KL\big(q(z|x)\,\|\,p(z|x)\big) = \int q(z|x)\ln \dfrac{q(z|x)}{p(z|x)}\, dz$

$\therefore \quad E_{q(z)}\big[\ln p(x)\big] = E_{q(z)}\Big[\ln \dfrac{p(x,z)}{q(z)}\Big] + KL\big(q(z)\,\|\,p(z|x)\big) \quad (7)$

$\therefore \quad$ 令 $ELBO = E_{q(z)}\Big[\ln \dfrac{p(x,z)}{q(z)}\Big]$，且由定义，$D_{KL} \geq 0$

$\therefore \quad E_{q(z)}\big[\ln p(x)\big] = ELBO + KL\big(q(z)\,\|\,p(z|x)\big) \quad (8)$

$\therefore \quad$ 当且仅当 $q(z) = q(z|x)$ 时，$E_{q(z)}\big[\ln p(x)\big] = ELBO$

在 VAE 中，需用 $q(z|x)$ 近似 $p(z|x)$

$\therefore \quad$ 此时 $E_{q(z)}\big[\ln p(x)\big] = ELBO$

故只须最大化 $ELBO$ 即可

由 (8)：$ELBO = E_{q(z)}\big[\ln p(x|z)\big] - KL\big(q(z)\,\|\,p(z)\big) \quad (9)$

$\therefore \quad$ 对于 $q(z)$，x 与 z 独立，故为了 encoder $q(z|x)$ 接近，将 $p(z)$ 改为 $q(z|x)$

$\therefore \quad ELBO = E_{q(z|x)}\big[\ln p(x|z)\big] - KL\big(q(z|x)\,\|\,p(z)\big) \quad (10)$

提高要求

为代码简洁与方便，提高要求部分仅使用mse构建损失函数。

提高要求1：实现VAE的变种

在这里选择实现beta-VAE。beta-VAE 是一种使用了自定义的 Kullback-Leibler divergence（KL 散度）来强化 VAE 的约束条件的模型。在 beta-VAE 中，自定义的 KL 散度表达式为：D_KL(q(z|x)||p(z)) = - beta D_KL(q(z|x)||p(z)) + (1 - beta) D_KL(p(z|x)||p(z))。其中，q(z|x) 表示 VAE 中的变分分布，p(z) 表示先验分布（例如标准正态分布），p(z|x) 表示 VAE 的重构分布，D_KL 表示KL 散度的计算公式，beta 是超参数。

在 beta-VAE 中，使用自定义的 KL 散度可以调节 VAE 的约束条件的强度。当 beta 值较小时，VAE 的约束条件较弱，解码的重构图像可能会更加复杂；当 beta 值较大时，VAE 的约束条件较强，解码的重构图像可能会更加简单。

具体到代码实现，只需加入超参数beta，在计算误差时将原来的loss = reconst_loss + kl_div 公式变为loss = reconst_loss + beta * kl_div即可。

查阅资料可知，超参数beta取值一般为1.0-4.0。由于beta取值为1.0时即为VAE，从略，下面分别讨论beta取值为2.0、3.0和4.0时的三种情况。

为简洁美观，在本部分中未变动代码部分注释将被删去，只注释变动部分，方便查看。下同。

beta=2.0

```
In [12]:
#创建新目录保存结果
sample_dir_mse_beta2 = 'advanced/beta_VAE/samples_mse_beta2'
if not os.path.exists(sample_dir_mse_beta2):
    os.makedirs(sample_dir_mse_beta2)

model = VAE().to(device)

optimizer = torch.optim.Adam(model.parameters(), lr=learning_rate)

#超参数beta
beta = 2.0

for epoch in range(num_epochs):
    for i, (x, _) in enumerate(data_loader):
        x = x.to(device).view(-1,image_size)
        x_reconst, mu, log_var = model(x)

        reconst_loss = F.mse_loss(x_reconst, x, size_average=False)
        # 自定义KL散度
        kl_div = - 0.5 * torch.sum(1 + log_var - mu.pow(2) - log_var.exp())
        kl_div = beta * kl_div

        loss = reconst_loss + kl_div

        optimizer.zero_grad()

        loss.backward()

        optimizer.step()

        if (i + 1) % 50 == 0:
            print("Epoch[{}/{}], Step [{}/{}], Reconst Loss(mse): {:.4f}, KL Div: {:
                  .format(epoch + 1, num_epochs, i + 1, len(data_loader), reconst_lo

    with torch.no_grad():
        # 改变保存路径
        z = torch.randn(batch_size, z_dim).to(device)
        out = model.decode(z).view(-1, 1, 28, 28)
        save_image(out, os.path.join(sample_dir_mse_beta2, 'sampled-{}.png'.format(e
        out, _, _ = model(x)
        x_concat = torch.cat([x.view(-1, 1, 28, 28), out.view(-1, 1, 28, 28)], dim=
        save_image(x_concat, os.path.join(sample_dir_mse_beta2, 'reconst-{}.png'.for
```

```
Epoch[1/15], Step [50/469], Reconst Loss(mse): 6882.8687, KL Div: 83.9953, Total Los
s: 6966.8638
Epoch[1/15], Step [100/469], Reconst Loss(mse): 6162.1074, KL Div: 303.2543, Total L
oss: 6465.3618
Epoch[1/15], Step [150/469], Reconst Loss(mse): 5793.8018, KL Div: 516.1176, Total L
oss: 6309.9194
Epoch[1/15], Step [200/469], Reconst Loss(mse): 5570.1294, KL Div: 708.6630, Total L
oss: 6278.7925
Epoch[1/15], Step [250/469], Reconst Loss(mse): 5242.6924, KL Div: 781.3737, Total L
oss: 6024.0659
Epoch[1/15], Step [300/469], Reconst Loss(mse): 5101.3135, KL Div: 957.2191, Total L
oss: 6058.5327
Epoch[1/15], Step [350/469], Reconst Loss(mse): 4950.3765, KL Div: 989.1937, Total L
oss: 5939.5703
Epoch[1/15], Step [400/469], Reconst Loss(mse): 4762.7905, KL Div: 1017.2475, Total
Loss: 5780.0381
Epoch[1/15], Step [450/469], Reconst Loss(mse): 4564.7910, KL Div: 1103.0527, Total
Loss: 5667.8438
Epoch[2/15], Step [50/469], Reconst Loss(mse): 4634.7363, KL Div: 1173.0780, Total L
oss: 5807.8145
Epoch[2/15], Step [100/469], Reconst Loss(mse): 4457.4141, KL Div: 1162.1906, Total
Loss: 5619.6045
Epoch[2/15], Step [150/469], Reconst Loss(mse): 4345.9180, KL Div: 1208.7954, Total
Loss: 5554.7134
Epoch[2/15], Step [200/469], Reconst Loss(mse): 4291.4492, KL Div: 1290.7185, Total
Loss: 5582.1680
Epoch[2/15], Step [250/469], Reconst Loss(mse): 4208.9365, KL Div: 1274.3207, Total
Loss: 5483.2573
Epoch[2/15], Step [300/469], Reconst Loss(mse): 4165.3779, KL Div: 1332.8613, Total
Loss: 5498.2393
Epoch[2/15], Step [350/469], Reconst Loss(mse): 4416.3555, KL Div: 1290.7284, Total
Loss: 5707.0840
Epoch[2/15], Step [400/469], Reconst Loss(mse): 4154.6475, KL Div: 1278.9812, Total
Loss: 5433.6289
Epoch[2/15], Step [450/469], Reconst Loss(mse): 4022.5811, KL Div: 1324.1567, Total
Loss: 5346.7378
Epoch[3/15], Step [50/469], Reconst Loss(mse): 4063.2476, KL Div: 1369.4462, Total L
oss: 5432.6938
Epoch[3/15], Step [100/469], Reconst Loss(mse): 4133.1221, KL Div: 1391.6539, Total
Loss: 5524.7759
Epoch[3/15], Step [150/469], Reconst Loss(mse): 3706.7009, KL Div: 1339.7852, Total
Loss: 5046.4863
Epoch[3/15], Step [200/469], Reconst Loss(mse): 4112.6631, KL Div: 1417.4822, Total
Loss: 5530.1455
Epoch[3/15], Step [250/469], Reconst Loss(mse): 3948.7524, KL Div: 1440.7067, Total
Loss: 5389.4590
Epoch[3/15], Step [300/469], Reconst Loss(mse): 3985.7827, KL Div: 1469.4823, Total
Loss: 5455.2651
Epoch[3/15], Step [350/469], Reconst Loss(mse): 3954.0991, KL Div: 1486.4342, Total
Loss: 5440.5332
Epoch[3/15], Step [400/469], Reconst Loss(mse): 4021.8755, KL Div: 1439.5164, Total
Loss: 5461.3916
Epoch[3/15], Step [450/469], Reconst Loss(mse): 3925.8872, KL Div: 1465.6414, Total
Loss: 5391.5283
Epoch[4/15], Step [50/469], Reconst Loss(mse): 3935.3611, KL Div: 1492.0526, Total L
oss: 5427.4136
Epoch[4/15], Step [100/469], Reconst Loss(mse): 3873.3218, KL Div: 1574.6033, Total
Loss: 5447.9248
Epoch[4/15], Step [150/469], Reconst Loss(mse): 4007.3696, KL Div: 1437.5520, Total
Loss: 5444.9219
Epoch[4/15], Step [200/469], Reconst Loss(mse): 3772.7834, KL Div: 1408.8269, Total
Loss: 5181.6104
Epoch[4/15], Step [250/469], Reconst Loss(mse): 3802.0273, KL Div: 1443.8920, Total
Loss: 5245.9194
```

Epoch[4/15], Step [300/469], Reconst Loss(mse): 3906.2271, KL Div: 1539.9238, Total Loss: 5446.1509

Epoch[4/15], Step [350/469], Reconst Loss(mse): 3640.2937, KL Div: 1500.9274, Total Loss: 5141.2212

Epoch[4/15], Step [400/469], Reconst Loss(mse): 3431.9180, KL Div: 1646.9871, Total Loss: 5078.9053

Epoch[4/15], Step [450/469], Reconst Loss(mse): 3555.6511, KL Div: 1470.9204, Total Loss: 5026.5713

Epoch[5/15], Step [50/469], Reconst Loss(mse): 3807.8179, KL Div: 1521.9196, Total Loss: 5329.7373

Epoch[5/15], Step [100/469], Reconst Loss(mse): 3774.5569, KL Div: 1589.7838, Total Loss: 5364.3408

Epoch[5/15], Step [150/469], Reconst Loss(mse): 3633.5352, KL Div: 1540.1798, Total Loss: 5173.7148

Epoch[5/15], Step [200/469], Reconst Loss(mse): 3672.8174, KL Div: 1487.1874, Total Loss: 5160.0049

Epoch[5/15], Step [250/469], Reconst Loss(mse): 3432.7092, KL Div: 1489.1808, Total Loss: 4921.8901

Epoch[5/15], Step [300/469], Reconst Loss(mse): 3745.6572, KL Div: 1539.3589, Total Loss: 5285.0161

Epoch[5/15], Step [350/469], Reconst Loss(mse): 3458.4949, KL Div: 1515.5491, Total Loss: 4974.0439

Epoch[5/15], Step [400/469], Reconst Loss(mse): 3404.6421, KL Div: 1588.5532, Total Loss: 4993.1953

Epoch[5/15], Step [450/469], Reconst Loss(mse): 3492.1401, KL Div: 1594.4503, Total Loss: 5086.5903

Epoch[6/15], Step [50/469], Reconst Loss(mse): 3600.0708, KL Div: 1630.0867, Total Loss: 5230.1572

Epoch[6/15], Step [100/469], Reconst Loss(mse): 3446.7915, KL Div: 1586.6152, Total Loss: 5033.4067

Epoch[6/15], Step [150/469], Reconst Loss(mse): 3457.1558, KL Div: 1518.5111, Total Loss: 4975.6670

Epoch[6/15], Step [200/469], Reconst Loss(mse): 3511.6860, KL Div: 1561.2576, Total Loss: 5072.9434

Epoch[6/15], Step [250/469], Reconst Loss(mse): 3739.2227, KL Div: 1488.5371, Total Loss: 5227.7598

Epoch[6/15], Step [300/469], Reconst Loss(mse): 3812.1948, KL Div: 1576.2039, Total Loss: 5388.3984

Epoch[6/15], Step [350/469], Reconst Loss(mse): 3585.6643, KL Div: 1639.5311, Total Loss: 5225.1953

Epoch[6/15], Step [400/469], Reconst Loss(mse): 3664.2300, KL Div: 1625.6776, Total Loss: 5289.9077

Epoch[6/15], Step [450/469], Reconst Loss(mse): 3451.7700, KL Div: 1544.0913, Total Loss: 4995.8613

Epoch[7/15], Step [50/469], Reconst Loss(mse): 3649.9148, KL Div: 1591.6290, Total Loss: 5241.5439

Epoch[7/15], Step [100/469], Reconst Loss(mse): 3656.6013, KL Div: 1559.9667, Total Loss: 5216.5679

Epoch[7/15], Step [150/469], Reconst Loss(mse): 3416.2468, KL Div: 1613.4072, Total Loss: 5029.6543

Epoch[7/15], Step [200/469], Reconst Loss(mse): 3506.5669, KL Div: 1541.2168, Total Loss: 5047.7837

Epoch[7/15], Step [250/469], Reconst Loss(mse): 3421.5225, KL Div: 1569.8702, Total Loss: 4991.3926

Epoch[7/15], Step [300/469], Reconst Loss(mse): 3714.9326, KL Div: 1592.7202, Total Loss: 5307.6528

Epoch[7/15], Step [350/469], Reconst Loss(mse): 3342.5366, KL Div: 1561.5214, Total Loss: 4904.0581

Epoch[7/15], Step [400/469], Reconst Loss(mse): 3317.0776, KL Div: 1638.5828, Total Loss: 4955.6602

Epoch[7/15], Step [450/469], Reconst Loss(mse): 3604.8567, KL Div: 1616.3411, Total Loss: 5221.1978

Epoch[8/15], Step [50/469], Reconst Loss(mse): 3636.9207, KL Div: 1575.3723, Total Loss: 5212.2930

Epoch[8/15], Step [100/469], Reconst Loss(mse): 3483.3223, KL Div: 1761.0028, Total Loss: 5244.3252

Epoch[8/15], Step [150/469], Reconst Loss(mse): 3333.7195, KL Div: 1635.1847, Total Loss: 4968.9043

Epoch[8/15], Step [200/469], Reconst Loss(mse): 3493.6511, KL Div: 1587.0319, Total Loss: 5080.6831

Epoch[8/15], Step [250/469], Reconst Loss(mse): 3526.7087, KL Div: 1521.8765, Total Loss: 5048.5850

Epoch[8/15], Step [300/469], Reconst Loss(mse): 3438.7908, KL Div: 1587.7876, Total Loss: 5026.5781

Epoch[8/15], Step [350/469], Reconst Loss(mse): 3418.6011, KL Div: 1600.0950, Total Loss: 5018.6963

Epoch[8/15], Step [400/469], Reconst Loss(mse): 3431.1318, KL Div: 1618.8629, Total Loss: 5049.9946

Epoch[8/15], Step [450/469], Reconst Loss(mse): 3273.3215, KL Div: 1661.6614, Total Loss: 4934.9829

Epoch[9/15], Step [50/469], Reconst Loss(mse): 3667.2998, KL Div: 1627.8933, Total Loss: 5295.1934

Epoch[9/15], Step [100/469], Reconst Loss(mse): 3401.0718, KL Div: 1641.2134, Total Loss: 5042.2852

Epoch[9/15], Step [150/469], Reconst Loss(mse): 3534.7280, KL Div: 1682.1410, Total Loss: 5216.8691

Epoch[9/15], Step [200/469], Reconst Loss(mse): 3552.0283, KL Div: 1567.9434, Total Loss: 5119.9717

Epoch[9/15], Step [250/469], Reconst Loss(mse): 3452.4182, KL Div: 1585.0896, Total Loss: 5037.5078

Epoch[9/15], Step [300/469], Reconst Loss(mse): 3444.0144, KL Div: 1608.2869, Total Loss: 5052.3013

Epoch[9/15], Step [350/469], Reconst Loss(mse): 3444.4407, KL Div: 1636.1415, Total Loss: 5080.5820

Epoch[9/15], Step [400/469], Reconst Loss(mse): 3299.6025, KL Div: 1567.0847, Total Loss: 4866.6875

Epoch[9/15], Step [450/469], Reconst Loss(mse): 3151.9600, KL Div: 1597.9263, Total Loss: 4749.8862

Epoch[10/15], Step [50/469], Reconst Loss(mse): 3491.5830, KL Div: 1610.9814, Total Loss: 5102.5645

Epoch[10/15], Step [100/469], Reconst Loss(mse): 3229.4385, KL Div: 1626.5127, Total Loss: 4855.9512

Epoch[10/15], Step [150/469], Reconst Loss(mse): 3315.4055, KL Div: 1543.7905, Total Loss: 4859.1963

Epoch[10/15], Step [200/469], Reconst Loss(mse): 3143.2969, KL Div: 1686.2504, Total Loss: 4829.5474

Epoch[10/15], Step [250/469], Reconst Loss(mse): 3168.0444, KL Div: 1593.2682, Total Loss: 4761.3125

Epoch[10/15], Step [300/469], Reconst Loss(mse): 3751.8030, KL Div: 1516.3466, Total Loss: 5268.1494

Epoch[10/15], Step [350/469], Reconst Loss(mse): 3334.2219, KL Div: 1579.9952, Total Loss: 4914.2173

Epoch[10/15], Step [400/469], Reconst Loss(mse): 3365.7981, KL Div: 1517.2756, Total Loss: 4883.0737

Epoch[10/15], Step [450/469], Reconst Loss(mse): 3357.2527, KL Div: 1635.8333, Total Loss: 4993.0859

Epoch[11/15], Step [50/469], Reconst Loss(mse): 3234.5173, KL Div: 1602.3949, Total Loss: 4836.9121

Epoch[11/15], Step [100/469], Reconst Loss(mse): 3314.5864, KL Div: 1705.2249, Total Loss: 5019.8115

Epoch[11/15], Step [150/469], Reconst Loss(mse): 3368.5190, KL Div: 1715.3567, Total Loss: 5083.8760

Epoch[11/15], Step [200/469], Reconst Loss(mse): 3535.0012, KL Div: 1696.1169, Total Loss: 5231.1182

Epoch[11/15], Step [250/469], Reconst Loss(mse): 3391.6318, KL Div: 1600.8035, Total Loss: 4992.4355

Epoch[11/15], Step [300/469], Reconst Loss(mse): 3514.8413, KL Div: 1612.3374, Total Loss: 5127.1787

Epoch[11/15], Step [350/469], Reconst Loss(mse): 3418.4924, KL Div: 1670.2776, Total
Loss: 5088.7700
Epoch[11/15], Step [400/469], Reconst Loss(mse): 3270.4863, KL Div: 1566.6556, Total
Loss: 4837.1421
Epoch[11/15], Step [450/469], Reconst Loss(mse): 3417.4043, KL Div: 1591.6711, Total
Loss: 5009.0752
Epoch[12/15], Step [50/469], Reconst Loss(mse): 3396.9316, KL Div: 1637.1537, Total
Loss: 5034.0854
Epoch[12/15], Step [100/469], Reconst Loss(mse): 3594.2761, KL Div: 1619.4163, Total
Loss: 5213.6924
Epoch[12/15], Step [150/469], Reconst Loss(mse): 3471.3992, KL Div: 1679.6857, Total
Loss: 5151.0850
Epoch[12/15], Step [200/469], Reconst Loss(mse): 3197.8167, KL Div: 1672.1783, Total
Loss: 4869.9951
Epoch[12/15], Step [250/469], Reconst Loss(mse): 3210.6240, KL Div: 1730.1355, Total
Loss: 4940.7598
Epoch[12/15], Step [300/469], Reconst Loss(mse): 3487.1309, KL Div: 1725.1981, Total
Loss: 5212.3291
Epoch[12/15], Step [350/469], Reconst Loss(mse): 3351.4805, KL Div: 1686.2253, Total
Loss: 5037.7061
Epoch[12/15], Step [400/469], Reconst Loss(mse): 3394.1213, KL Div: 1640.6742, Total
Loss: 5034.7954
Epoch[12/15], Step [450/469], Reconst Loss(mse): 3351.6833, KL Div: 1634.1359, Total
Loss: 4985.8193
Epoch[13/15], Step [50/469], Reconst Loss(mse): 3456.2722, KL Div: 1731.0220, Total
Loss: 5187.2939
Epoch[13/15], Step [100/469], Reconst Loss(mse): 3494.9165, KL Div: 1616.7552, Total
Loss: 5111.6719
Epoch[13/15], Step [150/469], Reconst Loss(mse): 3470.7485, KL Div: 1696.8910, Total
Loss: 5167.6396
Epoch[13/15], Step [200/469], Reconst Loss(mse): 3428.1350, KL Div: 1666.8580, Total
Loss: 5094.9932
Epoch[13/15], Step [250/469], Reconst Loss(mse): 3184.7031, KL Div: 1655.6667, Total
Loss: 4840.3701
Epoch[13/15], Step [300/469], Reconst Loss(mse): 3459.3979, KL Div: 1659.7410, Total
Loss: 5119.1387
Epoch[13/15], Step [350/469], Reconst Loss(mse): 3274.7283, KL Div: 1655.9940, Total
Loss: 4930.7222
Epoch[13/15], Step [400/469], Reconst Loss(mse): 3138.6245, KL Div: 1748.5347, Total
Loss: 4887.1592
Epoch[13/15], Step [450/469], Reconst Loss(mse): 3389.5510, KL Div: 1690.2280, Total
Loss: 5079.7793
Epoch[14/15], Step [50/469], Reconst Loss(mse): 3246.5862, KL Div: 1683.8975, Total
Loss: 4930.4834
Epoch[14/15], Step [100/469], Reconst Loss(mse): 3355.3403, KL Div: 1685.3649, Total
Loss: 5040.7051
Epoch[14/15], Step [150/469], Reconst Loss(mse): 3317.0383, KL Div: 1746.5596, Total
Loss: 5063.5977
Epoch[14/15], Step [200/469], Reconst Loss(mse): 3310.9534, KL Div: 1681.6946, Total
Loss: 4992.6479
Epoch[14/15], Step [250/469], Reconst Loss(mse): 3137.3416, KL Div: 1738.5375, Total
Loss: 4875.8789
Epoch[14/15], Step [300/469], Reconst Loss(mse): 3370.4043, KL Div: 1730.1895, Total
Loss: 5100.5938
Epoch[14/15], Step [350/469], Reconst Loss(mse): 3313.6890, KL Div: 1662.2777, Total
Loss: 4975.9668
Epoch[14/15], Step [400/469], Reconst Loss(mse): 3251.6643, KL Div: 1634.6588, Total
Loss: 4886.3232
Epoch[14/15], Step [450/469], Reconst Loss(mse): 3285.9038, KL Div: 1715.7448, Total
Loss: 5001.6484
Epoch[15/15], Step [50/469], Reconst Loss(mse): 3186.6152, KL Div: 1770.1792, Total
Loss: 4956.7944
Epoch[15/15], Step [100/469], Reconst Loss(mse): 3146.3169, KL Div: 1729.3210, Total
Loss: 4875.6377

```
Epoch[15/15], Step [150/469], Reconst Loss(mse): 3426.3293, KL Div: 1636.0009, Total
Loss: 5062.3301
Epoch[15/15], Step [200/469], Reconst Loss(mse): 3386.6523, KL Div: 1715.0997, Total
Loss: 5101.7520
Epoch[15/15], Step [250/469], Reconst Loss(mse): 3219.6438, KL Div: 1695.1919, Total
Loss: 4914.8359
Epoch[15/15], Step [300/469], Reconst Loss(mse): 3268.0166, KL Div: 1642.3994, Total
Loss: 4910.4160
Epoch[15/15], Step [350/469], Reconst Loss(mse): 3233.5493, KL Div: 1670.6318, Total
Loss: 4904.1812
Epoch[15/15], Step [400/469], Reconst Loss(mse): 3452.5322, KL Div: 1779.1024, Total
Loss: 5231.6348
Epoch[15/15], Step [450/469], Reconst Loss(mse): 3250.2085, KL Div: 1681.8574, Total
Loss: 4932.0659
```

beta=3.0

In [13]:
```python
#创建新目录保存结果
sample_dir_mse_beta3 = 'advanced/beta_VAE/samples_mse_beta3'
if not os.path.exists(sample_dir_mse_beta3):
    os.makedirs(sample_dir_mse_beta3)

model = VAE().to(device)

optimizer = torch.optim.Adam(model.parameters(), lr=learning_rate)

#超参数beta
beta = 3.0

for epoch in range(num_epochs):
    for i, (x, _) in enumerate(data_loader):
        x = x.to(device).view(-1,image_size)
        x_reconst, mu, log_var = model(x)

        reconst_loss = F.mse_loss(x_reconst, x, size_average=False)
        # 自定义KL散度
        kl_div = - 0.5 * torch.sum(1 + log_var - mu.pow(2) - log_var.exp())
        kl_div = beta * kl_div

        loss = reconst_loss + kl_div

        optimizer.zero_grad()

        loss.backward()

        optimizer.step()

        if (i + 1) % 50 == 0:
            print("Epoch[{}/{}], Step [{}/{}], Reconst Loss(mse): {:.4f}, KL Div: {:
                  .format(epoch + 1, num_epochs, i + 1, len(data_loader), reconst_lc

    with torch.no_grad():
        # 改变保存路径
        z = torch.randn(batch_size, z_dim).to(device)
        out = model.decode(z).view(-1, 1, 28, 28)
        save_image(out, os.path.join(sample_dir_mse_beta3, 'sampled-{}.png'.format(e
        out, _, _ = model(x)
        x_concat = torch.cat([x.view(-1, 1, 28, 28), out.view(-1, 1, 28, 28)], dim=
        save_image(x_concat, os.path.join(sample_dir_mse_beta3, 'reconst-{}.png'.for
```

Epoch[1/15], Step [50/469], Reconst Loss(mse): 6949.1338, KL Div: 51.3836, Total Loss: 7000.5176
Epoch[1/15], Step [100/469], Reconst Loss(mse): 6746.3647, KL Div: 92.0626, Total Loss: 6838.4272
Epoch[1/15], Step [150/469], Reconst Loss(mse): 6391.7490, KL Div: 289.6360, Total Loss: 6681.3848
Epoch[1/15], Step [200/469], Reconst Loss(mse): 6149.4678, KL Div: 419.2592, Total Loss: 6568.7271
Epoch[1/15], Step [250/469], Reconst Loss(mse): 5888.3672, KL Div: 543.5140, Total Loss: 6431.8813
Epoch[1/15], Step [300/469], Reconst Loss(mse): 5473.0894, KL Div: 650.7188, Total Loss: 6123.8081
Epoch[1/15], Step [350/469], Reconst Loss(mse): 5502.8989, KL Div: 728.5730, Total Loss: 6231.4717
Epoch[1/15], Step [400/469], Reconst Loss(mse): 5963.5820, KL Div: 766.3141, Total Loss: 6729.8960
Epoch[1/15], Step [450/469], Reconst Loss(mse): 5229.5342, KL Div: 858.2072, Total Loss: 6087.7412
Epoch[2/15], Step [50/469], Reconst Loss(mse): 5334.2959, KL Div: 970.3969, Total Loss: 6304.6929
Epoch[2/15], Step [100/469], Reconst Loss(mse): 5206.4824, KL Div: 968.3912, Total Loss: 6174.8735
Epoch[2/15], Step [150/469], Reconst Loss(mse): 5142.6870, KL Div: 958.0029, Total Loss: 6100.6899
Epoch[2/15], Step [200/469], Reconst Loss(mse): 5138.7861, KL Div: 1034.5939, Total Loss: 6173.3799
Epoch[2/15], Step [250/469], Reconst Loss(mse): 5176.0601, KL Div: 1055.1492, Total Loss: 6231.2090
Epoch[2/15], Step [300/469], Reconst Loss(mse): 4836.4893, KL Div: 1117.6311, Total Loss: 5954.1201
Epoch[2/15], Step [350/469], Reconst Loss(mse): 5176.0620, KL Div: 989.4856, Total Loss: 6165.5479
Epoch[2/15], Step [400/469], Reconst Loss(mse): 4684.5371, KL Div: 1075.1733, Total Loss: 5759.7104
Epoch[2/15], Step [450/469], Reconst Loss(mse): 4748.9224, KL Div: 1203.2317, Total Loss: 5952.1543
Epoch[3/15], Step [50/469], Reconst Loss(mse): 4808.8652, KL Div: 1212.5270, Total Loss: 6021.3921
Epoch[3/15], Step [100/469], Reconst Loss(mse): 4798.8076, KL Div: 1133.2461, Total Loss: 5932.0537
Epoch[3/15], Step [150/469], Reconst Loss(mse): 4783.1914, KL Div: 1258.1676, Total Loss: 6041.3589
Epoch[3/15], Step [200/469], Reconst Loss(mse): 4637.0986, KL Div: 1193.9507, Total Loss: 5831.0493
Epoch[3/15], Step [250/469], Reconst Loss(mse): 4657.3174, KL Div: 1253.5099, Total Loss: 5910.8271
Epoch[3/15], Step [300/469], Reconst Loss(mse): 4593.0908, KL Div: 1332.2886, Total Loss: 5925.3794
Epoch[3/15], Step [350/469], Reconst Loss(mse): 4391.7637, KL Div: 1261.5063, Total Loss: 5653.2700
Epoch[3/15], Step [400/469], Reconst Loss(mse): 4557.1338, KL Div: 1269.3511, Total Loss: 5826.4849
Epoch[3/15], Step [450/469], Reconst Loss(mse): 4572.7344, KL Div: 1304.0596, Total Loss: 5876.7939
Epoch[4/15], Step [50/469], Reconst Loss(mse): 4661.0073, KL Div: 1325.4124, Total Loss: 5986.4199
Epoch[4/15], Step [100/469], Reconst Loss(mse): 4390.2002, KL Div: 1209.2295, Total Loss: 5599.4297
Epoch[4/15], Step [150/469], Reconst Loss(mse): 4542.8066, KL Div: 1248.3807, Total Loss: 5791.1875
Epoch[4/15], Step [200/469], Reconst Loss(mse): 4564.5371, KL Div: 1341.1014, Total Loss: 5905.6387
Epoch[4/15], Step [250/469], Reconst Loss(mse): 4532.3384, KL Div: 1285.3605, Total Loss: 5817.6987

Epoch[4/15], Step [300/469], Reconst Loss(mse): 4520.7148, KL Div: 1298.9547, Total Loss: 5819.6694
Epoch[4/15], Step [350/469], Reconst Loss(mse): 4370.4233, KL Div: 1378.6134, Total Loss: 5749.0366
Epoch[4/15], Step [400/469], Reconst Loss(mse): 4552.4404, KL Div: 1276.2534, Total Loss: 5828.6938
Epoch[4/15], Step [450/469], Reconst Loss(mse): 4525.9355, KL Div: 1370.4359, Total Loss: 5896.3716
Epoch[5/15], Step [50/469], Reconst Loss(mse): 4659.0137, KL Div: 1334.3054, Total Loss: 5993.3193
Epoch[5/15], Step [100/469], Reconst Loss(mse): 4219.7061, KL Div: 1399.4664, Total Loss: 5619.1724
Epoch[5/15], Step [150/469], Reconst Loss(mse): 4293.8281, KL Div: 1345.7311, Total Loss: 5639.5591
Epoch[5/15], Step [200/469], Reconst Loss(mse): 4498.7207, KL Div: 1385.3008, Total Loss: 5884.0215
Epoch[5/15], Step [250/469], Reconst Loss(mse): 4559.1626, KL Div: 1419.5981, Total Loss: 5978.7607
Epoch[5/15], Step [300/469], Reconst Loss(mse): 4251.5786, KL Div: 1438.8441, Total Loss: 5690.4229
Epoch[5/15], Step [350/469], Reconst Loss(mse): 4339.1719, KL Div: 1348.2677, Total Loss: 5687.4395
Epoch[5/15], Step [400/469], Reconst Loss(mse): 3993.4448, KL Div: 1358.3081, Total Loss: 5351.7529
Epoch[5/15], Step [450/469], Reconst Loss(mse): 4349.0820, KL Div: 1491.4722, Total Loss: 5840.5542
Epoch[6/15], Step [50/469], Reconst Loss(mse): 4394.9375, KL Div: 1347.7489, Total Loss: 5742.6865
Epoch[6/15], Step [100/469], Reconst Loss(mse): 4491.0635, KL Div: 1428.0099, Total Loss: 5919.0732
Epoch[6/15], Step [150/469], Reconst Loss(mse): 4518.5566, KL Div: 1392.9677, Total Loss: 5911.5244
Epoch[6/15], Step [200/469], Reconst Loss(mse): 4413.4194, KL Div: 1394.2786, Total Loss: 5807.6982
Epoch[6/15], Step [250/469], Reconst Loss(mse): 4145.5571, KL Div: 1421.7622, Total Loss: 5567.3193
Epoch[6/15], Step [300/469], Reconst Loss(mse): 4304.9443, KL Div: 1495.3768, Total Loss: 5800.3213
Epoch[6/15], Step [350/469], Reconst Loss(mse): 4276.0518, KL Div: 1499.8357, Total Loss: 5775.8877
Epoch[6/15], Step [400/469], Reconst Loss(mse): 4280.9956, KL Div: 1282.3508, Total Loss: 5563.3467
Epoch[6/15], Step [450/469], Reconst Loss(mse): 4063.3557, KL Div: 1411.7604, Total Loss: 5475.1162
Epoch[7/15], Step [50/469], Reconst Loss(mse): 4385.4448, KL Div: 1420.5619, Total Loss: 5806.0068
Epoch[7/15], Step [100/469], Reconst Loss(mse): 4106.6113, KL Div: 1408.2178, Total Loss: 5514.8291
Epoch[7/15], Step [150/469], Reconst Loss(mse): 4054.5386, KL Div: 1492.3541, Total Loss: 5546.8926
Epoch[7/15], Step [200/469], Reconst Loss(mse): 4190.3516, KL Div: 1441.0579, Total Loss: 5631.4092
Epoch[7/15], Step [250/469], Reconst Loss(mse): 4278.6006, KL Div: 1475.6332, Total Loss: 5754.2339
Epoch[7/15], Step [300/469], Reconst Loss(mse): 4264.2231, KL Div: 1401.4939, Total Loss: 5665.7168
Epoch[7/15], Step [350/469], Reconst Loss(mse): 4249.2578, KL Div: 1452.9167, Total Loss: 5702.1748
Epoch[7/15], Step [400/469], Reconst Loss(mse): 4367.3750, KL Div: 1466.3828, Total Loss: 5833.7578
Epoch[7/15], Step [450/469], Reconst Loss(mse): 4239.4888, KL Div: 1518.8856, Total Loss: 5758.3745
Epoch[8/15], Step [50/469], Reconst Loss(mse): 4259.8740, KL Div: 1450.0044, Total Loss: 5709.8784

Epoch[8/15], Step [100/469], Reconst Loss(mse): 4473.5977, KL Div: 1537.8746, Total Loss: 6011.4722
Epoch[8/15], Step [150/469], Reconst Loss(mse): 4040.8950, KL Div: 1407.0660, Total Loss: 5447.9609
Epoch[8/15], Step [200/469], Reconst Loss(mse): 4483.4209, KL Div: 1522.1886, Total Loss: 6005.6094
Epoch[8/15], Step [250/469], Reconst Loss(mse): 4176.0952, KL Div: 1485.8065, Total Loss: 5661.9019
Epoch[8/15], Step [300/469], Reconst Loss(mse): 4144.6958, KL Div: 1541.2090, Total Loss: 5685.9048
Epoch[8/15], Step [350/469], Reconst Loss(mse): 4105.7690, KL Div: 1419.1466, Total Loss: 5524.9155
Epoch[8/15], Step [400/469], Reconst Loss(mse): 4355.1504, KL Div: 1370.0908, Total Loss: 5725.2412
Epoch[8/15], Step [450/469], Reconst Loss(mse): 4150.6123, KL Div: 1426.8175, Total Loss: 5577.4297
Epoch[9/15], Step [50/469], Reconst Loss(mse): 4257.3105, KL Div: 1418.7120, Total Loss: 5676.0225
Epoch[9/15], Step [100/469], Reconst Loss(mse): 4112.0566, KL Div: 1443.0757, Total Loss: 5555.1323
Epoch[9/15], Step [150/469], Reconst Loss(mse): 4041.6460, KL Div: 1522.9744, Total Loss: 5564.6201
Epoch[9/15], Step [200/469], Reconst Loss(mse): 4040.6594, KL Div: 1503.1101, Total Loss: 5543.7695
Epoch[9/15], Step [250/469], Reconst Loss(mse): 4475.3081, KL Div: 1393.7283, Total Loss: 5869.0361
Epoch[9/15], Step [300/469], Reconst Loss(mse): 4083.8191, KL Div: 1491.6943, Total Loss: 5575.5137
Epoch[9/15], Step [350/469], Reconst Loss(mse): 4257.9814, KL Div: 1508.1862, Total Loss: 5766.1675
Epoch[9/15], Step [400/469], Reconst Loss(mse): 4281.9897, KL Div: 1497.6998, Total Loss: 5779.6895
Epoch[9/15], Step [450/469], Reconst Loss(mse): 4508.2012, KL Div: 1531.8654, Total Loss: 6040.0664
Epoch[10/15], Step [50/469], Reconst Loss(mse): 3869.7961, KL Div: 1518.8610, Total Loss: 5388.6572
Epoch[10/15], Step [100/469], Reconst Loss(mse): 4236.7178, KL Div: 1550.8152, Total Loss: 5787.5332
Epoch[10/15], Step [150/469], Reconst Loss(mse): 4090.0344, KL Div: 1498.3369, Total Loss: 5588.3711
Epoch[10/15], Step [200/469], Reconst Loss(mse): 4256.6704, KL Div: 1543.8652, Total Loss: 5800.5356
Epoch[10/15], Step [250/469], Reconst Loss(mse): 4019.6074, KL Div: 1476.7589, Total Loss: 5496.3662
Epoch[10/15], Step [300/469], Reconst Loss(mse): 4166.8828, KL Div: 1513.8987, Total Loss: 5680.7812
Epoch[10/15], Step [350/469], Reconst Loss(mse): 4123.7324, KL Div: 1492.7443, Total Loss: 5616.4766
Epoch[10/15], Step [400/469], Reconst Loss(mse): 4004.0820, KL Div: 1505.0474, Total Loss: 5509.1294
Epoch[10/15], Step [450/469], Reconst Loss(mse): 4151.0918, KL Div: 1514.4203, Total Loss: 5665.5122
Epoch[11/15], Step [50/469], Reconst Loss(mse): 4254.1523, KL Div: 1473.3770, Total Loss: 5727.5293
Epoch[11/15], Step [100/469], Reconst Loss(mse): 4315.4419, KL Div: 1526.0648, Total Loss: 5841.5068
Epoch[11/15], Step [150/469], Reconst Loss(mse): 4007.2983, KL Div: 1508.8589, Total Loss: 5516.1572
Epoch[11/15], Step [200/469], Reconst Loss(mse): 3795.7705, KL Div: 1514.8073, Total Loss: 5310.5776
Epoch[11/15], Step [250/469], Reconst Loss(mse): 4079.9946, KL Div: 1536.3118, Total Loss: 5616.3066
Epoch[11/15], Step [300/469], Reconst Loss(mse): 4224.7749, KL Div: 1584.6824, Total Loss: 5809.4570

Epoch[11/15], Step [350/469], Reconst Loss(mse): 4115.6621, KL Div: 1582.4990, Total Loss: 5698.1611
Epoch[11/15], Step [400/469], Reconst Loss(mse): 4113.6436, KL Div: 1520.4115, Total Loss: 5634.0552
Epoch[11/15], Step [450/469], Reconst Loss(mse): 4071.7300, KL Div: 1679.0013, Total Loss: 5750.7314
Epoch[12/15], Step [50/469], Reconst Loss(mse): 4249.5859, KL Div: 1595.9541, Total Loss: 5845.5400
Epoch[12/15], Step [100/469], Reconst Loss(mse): 4030.8533, KL Div: 1514.7701, Total Loss: 5545.6235
Epoch[12/15], Step [150/469], Reconst Loss(mse): 4156.6592, KL Div: 1452.4873, Total Loss: 5609.1465
Epoch[12/15], Step [200/469], Reconst Loss(mse): 3938.9917, KL Div: 1563.6746, Total Loss: 5502.6660
Epoch[12/15], Step [250/469], Reconst Loss(mse): 4099.1914, KL Div: 1609.7224, Total Loss: 5708.9141
Epoch[12/15], Step [300/469], Reconst Loss(mse): 3979.4968, KL Div: 1550.9802, Total Loss: 5530.4771
Epoch[12/15], Step [350/469], Reconst Loss(mse): 3879.6748, KL Div: 1522.9546, Total Loss: 5402.6294
Epoch[12/15], Step [400/469], Reconst Loss(mse): 3811.4182, KL Div: 1571.0562, Total Loss: 5382.4746
Epoch[12/15], Step [450/469], Reconst Loss(mse): 4267.5000, KL Div: 1452.4766, Total Loss: 5719.9766
Epoch[13/15], Step [50/469], Reconst Loss(mse): 4225.9453, KL Div: 1628.5793, Total Loss: 5854.5244
Epoch[13/15], Step [100/469], Reconst Loss(mse): 4101.5176, KL Div: 1570.1327, Total Loss: 5671.6504
Epoch[13/15], Step [150/469], Reconst Loss(mse): 4040.3215, KL Div: 1482.8252, Total Loss: 5523.1465
Epoch[13/15], Step [200/469], Reconst Loss(mse): 4093.5811, KL Div: 1524.1914, Total Loss: 5617.7725
Epoch[13/15], Step [250/469], Reconst Loss(mse): 3865.8794, KL Div: 1582.8774, Total Loss: 5448.7568
Epoch[13/15], Step [300/469], Reconst Loss(mse): 4308.8540, KL Div: 1480.1853, Total Loss: 5789.0391
Epoch[13/15], Step [350/469], Reconst Loss(mse): 4048.2139, KL Div: 1522.0275, Total Loss: 5570.2412
Epoch[13/15], Step [400/469], Reconst Loss(mse): 4271.6802, KL Div: 1594.3164, Total Loss: 5865.9966
Epoch[13/15], Step [450/469], Reconst Loss(mse): 3836.3315, KL Div: 1591.2689, Total Loss: 5427.6006
Epoch[14/15], Step [50/469], Reconst Loss(mse): 3923.3201, KL Div: 1689.6991, Total Loss: 5613.0190
Epoch[14/15], Step [100/469], Reconst Loss(mse): 3940.4902, KL Div: 1490.2029, Total Loss: 5430.6934
Epoch[14/15], Step [150/469], Reconst Loss(mse): 4068.8982, KL Div: 1619.0903, Total Loss: 5687.9883
Epoch[14/15], Step [200/469], Reconst Loss(mse): 4143.7900, KL Div: 1569.1842, Total Loss: 5712.9741
Epoch[14/15], Step [250/469], Reconst Loss(mse): 3986.8208, KL Div: 1611.4280, Total Loss: 5598.2490
Epoch[14/15], Step [300/469], Reconst Loss(mse): 4155.6401, KL Div: 1516.9678, Total Loss: 5672.6079
Epoch[14/15], Step [350/469], Reconst Loss(mse): 3934.7847, KL Div: 1626.8091, Total Loss: 5561.5938
Epoch[14/15], Step [400/469], Reconst Loss(mse): 4054.5837, KL Div: 1497.5942, Total Loss: 5552.1777
Epoch[14/15], Step [450/469], Reconst Loss(mse): 4095.4336, KL Div: 1514.5712, Total Loss: 5610.0049
Epoch[15/15], Step [50/469], Reconst Loss(mse): 4123.2280, KL Div: 1581.1307, Total Loss: 5704.3589
Epoch[15/15], Step [100/469], Reconst Loss(mse): 4039.3591, KL Div: 1652.7568, Total Loss: 5692.1162

```
Epoch[15/15], Step [150/469], Reconst Loss(mse): 4103.7490, KL Div: 1534.1185, Total
Loss: 5637.8677
Epoch[15/15], Step [200/469], Reconst Loss(mse): 3941.2537, KL Div: 1536.0605, Total
Loss: 5477.3145
Epoch[15/15], Step [250/469], Reconst Loss(mse): 3885.9355, KL Div: 1576.4033, Total
Loss: 5462.3389
Epoch[15/15], Step [300/469], Reconst Loss(mse): 3979.8320, KL Div: 1578.7170, Total
Loss: 5558.5488
Epoch[15/15], Step [350/469], Reconst Loss(mse): 3981.8242, KL Div: 1576.8804, Total
Loss: 5558.7046
Epoch[15/15], Step [400/469], Reconst Loss(mse): 4297.9126, KL Div: 1529.9119, Total
Loss: 5827.8242
Epoch[15/15], Step [450/469], Reconst Loss(mse): 4190.0815, KL Div: 1580.8195, Total
Loss: 5770.9009
```

beta=4.0

In [14]:
```python
#创建新目录保存结果
sample_dir_mse_beta4 = 'advanced/beta_VAE/samples_mse_beta4'
if not os.path.exists(sample_dir_mse_beta4):
    os.makedirs(sample_dir_mse_beta4)

model = VAE().to(device)

optimizer = torch.optim.Adam(model.parameters(), lr=learning_rate)

#超参数beta
beta = 4.0

for epoch in range(num_epochs):
    for i, (x, _) in enumerate(data_loader):
        x = x.to(device).view(-1,image_size)
        x_reconst, mu, log_var = model(x)

        reconst_loss = F.mse_loss(x_reconst, x, size_average=False)
        # 自定义KL散度
        kl_div = - 0.5 * torch.sum(1 + log_var - mu.pow(2) - log_var.exp())
        kl_div = beta * kl_div

        loss = reconst_loss + kl_div

        optimizer.zero_grad()

        loss.backward()

        optimizer.step()

        if (i + 1) % 50 == 0:
            print("Epoch[{}/{}], Step [{}/{}], Reconst Loss(mse): {:.4f}, KL Div: {:
                  .format(epoch + 1, num_epochs, i + 1, len(data_loader), reconst_lo

    with torch.no_grad():
        # 改变保存路径
        z = torch.randn(batch_size, z_dim).to(device)
        out = model.decode(z).view(-1, 1, 28, 28)
        save_image(out, os.path.join(sample_dir_mse_beta4, 'sampled-{}.png'.format(e
        out, _, _ = model(x)
        x_concat = torch.cat([x.view(-1, 1, 28, 28), out.view(-1, 1, 28, 28)], dim=
        save_image(x_concat, os.path.join(sample_dir_mse_beta4, 'reconst-{}.png'.for
```

```
Epoch[1/15], Step [50/469], Reconst Loss(mse): 6727.6816, KL Div: 43.6697, Total Los
s: 6771.3516
Epoch[1/15], Step [100/469], Reconst Loss(mse): 6632.5908, KL Div: 102.6924, Total L
oss: 6735.2832
Epoch[1/15], Step [150/469], Reconst Loss(mse): 6717.6885, KL Div: 185.1254, Total L
oss: 6902.8140
Epoch[1/15], Step [200/469], Reconst Loss(mse): 6151.7539, KL Div: 336.1330, Total L
oss: 6487.8867
Epoch[1/15], Step [250/469], Reconst Loss(mse): 6440.7261, KL Div: 329.4766, Total L
oss: 6770.2026
Epoch[1/15], Step [300/469], Reconst Loss(mse): 6153.4189, KL Div: 390.7791, Total L
oss: 6544.1982
Epoch[1/15], Step [350/469], Reconst Loss(mse): 5967.6929, KL Div: 442.2342, Total L
oss: 6409.9272
Epoch[1/15], Step [400/469], Reconst Loss(mse): 5985.0469, KL Div: 561.6875, Total L
oss: 6546.7344
Epoch[1/15], Step [450/469], Reconst Loss(mse): 5768.0679, KL Div: 703.1777, Total L
oss: 6471.2456
Epoch[2/15], Step [50/469], Reconst Loss(mse): 5837.5669, KL Div: 611.3806, Total Lo
ss: 6448.9473
Epoch[2/15], Step [100/469], Reconst Loss(mse): 5882.5776, KL Div: 714.9703, Total L
oss: 6597.5479
Epoch[2/15], Step [150/469], Reconst Loss(mse): 5743.7109, KL Div: 617.5261, Total L
oss: 6361.2368
Epoch[2/15], Step [200/469], Reconst Loss(mse): 5524.2236, KL Div: 737.1928, Total L
oss: 6261.4165
Epoch[2/15], Step [250/469], Reconst Loss(mse): 5637.2041, KL Div: 715.1613, Total L
oss: 6352.3652
Epoch[2/15], Step [300/469], Reconst Loss(mse): 5775.2588, KL Div: 900.2110, Total L
oss: 6675.4697
Epoch[2/15], Step [350/469], Reconst Loss(mse): 5741.7051, KL Div: 820.1726, Total L
oss: 6561.8779
Epoch[2/15], Step [400/469], Reconst Loss(mse): 5510.5269, KL Div: 830.0034, Total L
oss: 6340.5303
Epoch[2/15], Step [450/469], Reconst Loss(mse): 5570.0889, KL Div: 841.9808, Total L
oss: 6412.0698
Epoch[3/15], Step [50/469], Reconst Loss(mse): 5447.9463, KL Div: 873.5353, Total Lo
ss: 6321.4814
Epoch[3/15], Step [100/469], Reconst Loss(mse): 5272.1948, KL Div: 945.8588, Total L
oss: 6218.0537
Epoch[3/15], Step [150/469], Reconst Loss(mse): 5310.5098, KL Div: 889.1271, Total L
oss: 6199.6367
Epoch[3/15], Step [200/469], Reconst Loss(mse): 5070.7329, KL Div: 973.3402, Total L
oss: 6044.0732
Epoch[3/15], Step [250/469], Reconst Loss(mse): 5368.3926, KL Div: 854.0931, Total L
oss: 6222.4858
Epoch[3/15], Step [300/469], Reconst Loss(mse): 5458.6602, KL Div: 979.6458, Total L
oss: 6438.3062
Epoch[3/15], Step [350/469], Reconst Loss(mse): 5226.2920, KL Div: 1076.5879, Total
Loss: 6302.8799
Epoch[3/15], Step [400/469], Reconst Loss(mse): 5416.5669, KL Div: 1082.6661, Total
Loss: 6499.2329
Epoch[3/15], Step [450/469], Reconst Loss(mse): 5056.9561, KL Div: 1121.5627, Total
Loss: 6178.5186
Epoch[4/15], Step [50/469], Reconst Loss(mse): 5379.6523, KL Div: 1028.9692, Total L
oss: 6408.6216
Epoch[4/15], Step [100/469], Reconst Loss(mse): 5048.6699, KL Div: 1081.7502, Total
Loss: 6130.4199
Epoch[4/15], Step [150/469], Reconst Loss(mse): 4914.6211, KL Div: 1143.0303, Total
Loss: 6057.6514
Epoch[4/15], Step [200/469], Reconst Loss(mse): 5137.8110, KL Div: 1153.6715, Total
Loss: 6291.4824
Epoch[4/15], Step [250/469], Reconst Loss(mse): 5129.8896, KL Div: 1070.9985, Total
Loss: 6200.8882
```

Epoch[4/15], Step [300/469], Reconst Loss(mse): 5033.9541, KL Div: 1170.2229, Total Loss: 6204.1768
Epoch[4/15], Step [350/469], Reconst Loss(mse): 5022.0078, KL Div: 1107.1423, Total Loss: 6129.1504
Epoch[4/15], Step [400/469], Reconst Loss(mse): 4980.9429, KL Div: 1144.3572, Total Loss: 6125.2998
Epoch[4/15], Step [450/469], Reconst Loss(mse): 5212.3887, KL Div: 1076.0276, Total Loss: 6288.4160
Epoch[5/15], Step [50/469], Reconst Loss(mse): 5139.4570, KL Div: 1176.4121, Total Loss: 6315.8691
Epoch[5/15], Step [100/469], Reconst Loss(mse): 5194.1641, KL Div: 1164.3424, Total Loss: 6358.5063
Epoch[5/15], Step [150/469], Reconst Loss(mse): 4929.8589, KL Div: 1178.6038, Total Loss: 6108.4629
Epoch[5/15], Step [200/469], Reconst Loss(mse): 4937.5112, KL Div: 1177.9429, Total Loss: 6115.4541
Epoch[5/15], Step [250/469], Reconst Loss(mse): 4930.0928, KL Div: 1156.3513, Total Loss: 6086.4443
Epoch[5/15], Step [300/469], Reconst Loss(mse): 5087.1797, KL Div: 1221.1680, Total Loss: 6308.3477
Epoch[5/15], Step [350/469], Reconst Loss(mse): 4828.6074, KL Div: 1284.5573, Total Loss: 6113.1646
Epoch[5/15], Step [400/469], Reconst Loss(mse): 4716.5825, KL Div: 1148.9308, Total Loss: 5865.5132
Epoch[5/15], Step [450/469], Reconst Loss(mse): 5190.6401, KL Div: 1108.6393, Total Loss: 6299.2793
Epoch[6/15], Step [50/469], Reconst Loss(mse): 4815.4712, KL Div: 1181.4800, Total Loss: 5996.9512
Epoch[6/15], Step [100/469], Reconst Loss(mse): 4936.3975, KL Div: 1189.3334, Total Loss: 6125.7310
Epoch[6/15], Step [150/469], Reconst Loss(mse): 4965.8955, KL Div: 1211.2034, Total Loss: 6177.0986
Epoch[6/15], Step [200/469], Reconst Loss(mse): 5017.0938, KL Div: 1236.3743, Total Loss: 6253.4678
Epoch[6/15], Step [250/469], Reconst Loss(mse): 4917.8936, KL Div: 1234.6611, Total Loss: 6152.5547
Epoch[6/15], Step [300/469], Reconst Loss(mse): 4854.1455, KL Div: 1240.9695, Total Loss: 6095.1152
Epoch[6/15], Step [350/469], Reconst Loss(mse): 4833.6836, KL Div: 1206.6250, Total Loss: 6040.3086
Epoch[6/15], Step [400/469], Reconst Loss(mse): 4715.5527, KL Div: 1206.7347, Total Loss: 5922.2876
Epoch[6/15], Step [450/469], Reconst Loss(mse): 4782.9570, KL Div: 1265.7244, Total Loss: 6048.6816
Epoch[7/15], Step [50/469], Reconst Loss(mse): 4849.3413, KL Div: 1298.5267, Total Loss: 6147.8682
Epoch[7/15], Step [100/469], Reconst Loss(mse): 4859.7896, KL Div: 1244.0278, Total Loss: 6103.8174
Epoch[7/15], Step [150/469], Reconst Loss(mse): 4968.3594, KL Div: 1223.4752, Total Loss: 6191.8345
Epoch[7/15], Step [200/469], Reconst Loss(mse): 4906.1250, KL Div: 1191.4326, Total Loss: 6097.5576
Epoch[7/15], Step [250/469], Reconst Loss(mse): 4650.2246, KL Div: 1290.5731, Total Loss: 5940.7979
Epoch[7/15], Step [300/469], Reconst Loss(mse): 4886.5107, KL Div: 1198.5884, Total Loss: 6085.0991
Epoch[7/15], Step [350/469], Reconst Loss(mse): 5176.6963, KL Div: 1223.0339, Total Loss: 6399.7305
Epoch[7/15], Step [400/469], Reconst Loss(mse): 4964.6504, KL Div: 1193.4918, Total Loss: 6158.1421
Epoch[7/15], Step [450/469], Reconst Loss(mse): 4371.1997, KL Div: 1364.9083, Total Loss: 5736.1079
Epoch[8/15], Step [50/469], Reconst Loss(mse): 4816.4199, KL Div: 1308.3215, Total Loss: 6124.7412

Epoch[8/15], Step [100/469], Reconst Loss(mse): 4546.3008, KL Div: 1317.9930, Total Loss: 5864.2939
Epoch[8/15], Step [150/469], Reconst Loss(mse): 5237.4263, KL Div: 1305.9319, Total Loss: 6543.3584
Epoch[8/15], Step [200/469], Reconst Loss(mse): 4947.8257, KL Div: 1295.2833, Total Loss: 6243.1089
Epoch[8/15], Step [250/469], Reconst Loss(mse): 4764.4336, KL Div: 1294.9142, Total Loss: 6059.3477
Epoch[8/15], Step [300/469], Reconst Loss(mse): 4829.1709, KL Div: 1388.9553, Total Loss: 6218.1260
Epoch[8/15], Step [350/469], Reconst Loss(mse): 4994.8691, KL Div: 1275.9565, Total Loss: 6270.8257
Epoch[8/15], Step [400/469], Reconst Loss(mse): 4993.8413, KL Div: 1328.2633, Total Loss: 6322.1045
Epoch[8/15], Step [450/469], Reconst Loss(mse): 4834.0771, KL Div: 1291.3469, Total Loss: 6125.4238
Epoch[9/15], Step [50/469], Reconst Loss(mse): 4635.0010, KL Div: 1437.0059, Total Loss: 6072.0068
Epoch[9/15], Step [100/469], Reconst Loss(mse): 4789.6729, KL Div: 1294.2081, Total Loss: 6083.8809
Epoch[9/15], Step [150/469], Reconst Loss(mse): 4791.7451, KL Div: 1217.8679, Total Loss: 6009.6133
Epoch[9/15], Step [200/469], Reconst Loss(mse): 4523.2354, KL Div: 1425.0540, Total Loss: 5948.2891
Epoch[9/15], Step [250/469], Reconst Loss(mse): 4745.3501, KL Div: 1396.1136, Total Loss: 6141.4639
Epoch[9/15], Step [300/469], Reconst Loss(mse): 4535.4165, KL Div: 1407.7859, Total Loss: 5943.2021
Epoch[9/15], Step [350/469], Reconst Loss(mse): 4833.5400, KL Div: 1325.9821, Total Loss: 6159.5220
Epoch[9/15], Step [400/469], Reconst Loss(mse): 4902.2236, KL Div: 1250.0065, Total Loss: 6152.2300
Epoch[9/15], Step [450/469], Reconst Loss(mse): 4970.8481, KL Div: 1182.5994, Total Loss: 6153.4473
Epoch[10/15], Step [50/469], Reconst Loss(mse): 4850.1592, KL Div: 1292.2825, Total Loss: 6142.4414
Epoch[10/15], Step [100/469], Reconst Loss(mse): 4577.5962, KL Div: 1459.6274, Total Loss: 6037.2236
Epoch[10/15], Step [150/469], Reconst Loss(mse): 4622.1504, KL Div: 1381.4448, Total Loss: 6003.5952
Epoch[10/15], Step [200/469], Reconst Loss(mse): 4514.5200, KL Div: 1398.6963, Total Loss: 5913.2163
Epoch[10/15], Step [250/469], Reconst Loss(mse): 5101.1030, KL Div: 1283.0264, Total Loss: 6384.1294
Epoch[10/15], Step [300/469], Reconst Loss(mse): 5090.9990, KL Div: 1387.6628, Total Loss: 6478.6621
Epoch[10/15], Step [350/469], Reconst Loss(mse): 5106.2412, KL Div: 1235.3315, Total Loss: 6341.5728
Epoch[10/15], Step [400/469], Reconst Loss(mse): 4821.3726, KL Div: 1260.0005, Total Loss: 6081.3730
Epoch[10/15], Step [450/469], Reconst Loss(mse): 4720.9355, KL Div: 1349.7826, Total Loss: 6070.7183
Epoch[11/15], Step [50/469], Reconst Loss(mse): 4886.5815, KL Div: 1272.2437, Total Loss: 6158.8252
Epoch[11/15], Step [100/469], Reconst Loss(mse): 4828.2578, KL Div: 1305.2115, Total Loss: 6133.4692
Epoch[11/15], Step [150/469], Reconst Loss(mse): 4784.2925, KL Div: 1320.8286, Total Loss: 6105.1211
Epoch[11/15], Step [200/469], Reconst Loss(mse): 4810.1621, KL Div: 1403.9822, Total Loss: 6214.1445
Epoch[11/15], Step [250/469], Reconst Loss(mse): 4661.1206, KL Div: 1371.0524, Total Loss: 6032.1729
Epoch[11/15], Step [300/469], Reconst Loss(mse): 4941.6392, KL Div: 1382.3416, Total Loss: 6323.9805

Epoch[11/15], Step [350/469], Reconst Loss(mse): 4743.3281, KL Div: 1359.9458, Total Loss: 6103.2739
Epoch[11/15], Step [400/469], Reconst Loss(mse): 4776.9521, KL Div: 1309.0671, Total Loss: 6086.0195
Epoch[11/15], Step [450/469], Reconst Loss(mse): 4673.0312, KL Div: 1285.2500, Total Loss: 5958.2812
Epoch[12/15], Step [50/469], Reconst Loss(mse): 4885.1621, KL Div: 1483.3524, Total Loss: 6368.5146
Epoch[12/15], Step [100/469], Reconst Loss(mse): 4905.6182, KL Div: 1314.5303, Total Loss: 6220.1484
Epoch[12/15], Step [150/469], Reconst Loss(mse): 4988.4829, KL Div: 1308.0497, Total Loss: 6296.5327
Epoch[12/15], Step [200/469], Reconst Loss(mse): 4578.0322, KL Div: 1406.0623, Total Loss: 5984.0947
Epoch[12/15], Step [250/469], Reconst Loss(mse): 4490.0601, KL Div: 1326.6726, Total Loss: 5816.7324
Epoch[12/15], Step [300/469], Reconst Loss(mse): 4983.5308, KL Div: 1314.2515, Total Loss: 6297.7822
Epoch[12/15], Step [350/469], Reconst Loss(mse): 4487.9634, KL Div: 1276.7876, Total Loss: 5764.7510
Epoch[12/15], Step [400/469], Reconst Loss(mse): 4720.2202, KL Div: 1392.7439, Total Loss: 6112.9639
Epoch[12/15], Step [450/469], Reconst Loss(mse): 4368.6660, KL Div: 1432.1814, Total Loss: 5800.8477
Epoch[13/15], Step [50/469], Reconst Loss(mse): 4590.0410, KL Div: 1388.1617, Total Loss: 5978.2026
Epoch[13/15], Step [100/469], Reconst Loss(mse): 4616.0532, KL Div: 1356.3864, Total Loss: 5972.4395
Epoch[13/15], Step [150/469], Reconst Loss(mse): 4570.6509, KL Div: 1362.7483, Total Loss: 5933.3994
Epoch[13/15], Step [200/469], Reconst Loss(mse): 4762.6138, KL Div: 1394.3575, Total Loss: 6156.9712
Epoch[13/15], Step [250/469], Reconst Loss(mse): 4822.4331, KL Div: 1318.1035, Total Loss: 6140.5366
Epoch[13/15], Step [300/469], Reconst Loss(mse): 4646.1704, KL Div: 1390.4006, Total Loss: 6036.5713
Epoch[13/15], Step [350/469], Reconst Loss(mse): 4726.7192, KL Div: 1371.8849, Total Loss: 6098.6040
Epoch[13/15], Step [400/469], Reconst Loss(mse): 4789.7695, KL Div: 1380.6323, Total Loss: 6170.4019
Epoch[13/15], Step [450/469], Reconst Loss(mse): 4663.3804, KL Div: 1345.4324, Total Loss: 6008.8125
Epoch[14/15], Step [50/469], Reconst Loss(mse): 4683.0859, KL Div: 1332.9546, Total Loss: 6016.0405
Epoch[14/15], Step [100/469], Reconst Loss(mse): 4811.8384, KL Div: 1342.6304, Total Loss: 6154.4688
Epoch[14/15], Step [150/469], Reconst Loss(mse): 4475.0469, KL Div: 1417.7098, Total Loss: 5892.7568
Epoch[14/15], Step [200/469], Reconst Loss(mse): 4624.5928, KL Div: 1376.9312, Total Loss: 6001.5239
Epoch[14/15], Step [250/469], Reconst Loss(mse): 5011.1592, KL Div: 1449.0496, Total Loss: 6460.2090
Epoch[14/15], Step [300/469], Reconst Loss(mse): 4610.8604, KL Div: 1400.5598, Total Loss: 6011.4199
Epoch[14/15], Step [350/469], Reconst Loss(mse): 5003.9580, KL Div: 1505.8490, Total Loss: 6509.8071
Epoch[14/15], Step [400/469], Reconst Loss(mse): 4677.3721, KL Div: 1389.1570, Total Loss: 6066.5293
Epoch[14/15], Step [450/469], Reconst Loss(mse): 4732.7549, KL Div: 1405.2766, Total Loss: 6138.0312
Epoch[15/15], Step [50/469], Reconst Loss(mse): 4296.7388, KL Div: 1422.9487, Total Loss: 5719.6875
Epoch[15/15], Step [100/469], Reconst Loss(mse): 4606.3467, KL Div: 1402.1323, Total Loss: 6008.4790

```
Epoch[15/15], Step [150/469], Reconst Loss(mse): 4805.9932, KL Div: 1354.5488, Total
Loss: 6160.5420
Epoch[15/15], Step [200/469], Reconst Loss(mse): 4811.2720, KL Div: 1405.0111, Total
Loss: 6216.2832
Epoch[15/15], Step [250/469], Reconst Loss(mse): 4760.5186, KL Div: 1381.6498, Total
Loss: 6142.1685
Epoch[15/15], Step [300/469], Reconst Loss(mse): 4467.2271, KL Div: 1367.9829, Total
Loss: 5835.2100
Epoch[15/15], Step [350/469], Reconst Loss(mse): 4595.7705, KL Div: 1300.9894, Total
Loss: 5896.7598
Epoch[15/15], Step [400/469], Reconst Loss(mse): 4783.7988, KL Div: 1407.0966, Total
Loss: 6190.8955
Epoch[15/15], Step [450/469], Reconst Loss(mse): 4861.1499, KL Div: 1385.6581, Total
Loss: 6246.8081
```

提高要求2：修改数据集以发掘VAE更多的功能

添加噪点

由于VAE模型使用pytorch库构建，而pytorch并没有直接在数据集中添加噪点的库函数。因此，在这里选择使用随机仿射变换函数实现添加噪点。

随机仿射变换是一种常见的图像变换方法，可以在保持图像内容不变的前提下，随机调整图像的尺度、旋转角度、平移位置等参数。

通常，随机仿射变换可以用来扩充训练数据集，增强模型的泛化能力。

但是，当随机仿射变换的参数设置得较大时，可能会产生噪点的效果。

具体来说，在使用 torchvision.transforms.RandomAffine 函数时，我们使用 translate 参数来设置平移的范围，当 translate 参数设置为较大的值时，图像会被平移较大的距离，导致图像中出现较多的噪点。

In [15]:
```python
#创建新目录保存结果
sample_dir_mse_noise = 'advanced/modified dataset/samples_mse_noise'
if not os.path.exists(sample_dir_mse_noise):
    os.makedirs(sample_dir_mse_noise)

#定义随机变换
transform_noise = transforms.Compose([
    transforms.ToTensor(),  # 将 PIL 图像转换为张量
    transforms.Normalize((0.5,), (0.5,)),  # 归一化
    transforms.RandomAffine(degrees=0,translate=(0.005, 0.005)),  # 随机仿射变换
])

#对数据集进行添加噪点
dataset_noise = torchvision.datasets.MNIST(root='./data',
                                           train=True,
                                           transform=transform_noise,
                                           download=True)

data_loader_noise = torch.utils.data.DataLoader(dataset=dataset_noise,
                                                batch_size=batch_size,
                                                shuffle=True)

model = VAE().to(device)

optimizer = torch.optim.Adam(model.parameters(), lr=learning_rate)
```

```python
beta = 1.0

for epoch in range(num_epochs):
    #使用添加噪点的数据集
    for i, (x, _) in enumerate(data_loader_noise):
        x = x.to(device).view(-1,image_size)
        x_reconst, mu, log_var = model(x)

        reconst_loss = F.mse_loss(x_reconst, x, size_average=False)

        kl_div = - 0.5 * torch.sum(1 + log_var - mu.pow(2) - log_var.exp())
        kl_div = beta * kl_div

        loss = reconst_loss + kl_div

        optimizer.zero_grad()

        loss.backward()

        optimizer.step()

        if (i + 1) % 50 == 0:
            print("Epoch[{}/{}], Step [{}/{}], Reconst Loss(mse): {:.4f}, KL Div: {:
                  .format(epoch + 1, num_epochs, i + 1, len(data_loader_noise), reco

    with torch.no_grad():
        # 改变保存路径
        z = torch.randn(batch_size, z_dim).to(device)
        out = model.decode(z).view(-1, 1, 28, 28)
        save_image(out, os.path.join(sample_dir_mse_noise, 'sampled-{}.png'.format(e
        out, _, _ = model(x)
        x_concat = torch.cat([x.view(-1, 1, 28, 28), out.view(-1, 1, 28, 28)], dim=
        save_image(x_concat, os.path.join(sample_dir_mse_noise, 'reconst-{}.png'.for
```

Epoch[1/15], Step [50/469], Reconst Loss(mse): 93391.5781, KL Div: 1362.7610, Total Loss: 94754.3359
Epoch[1/15], Step [100/469], Reconst Loss(mse): 93249.2891, KL Div: 927.4186, Total Loss: 94176.7109
Epoch[1/15], Step [150/469], Reconst Loss(mse): 93102.4375, KL Div: 798.4313, Total Loss: 93900.8672
Epoch[1/15], Step [200/469], Reconst Loss(mse): 92827.4375, KL Div: 542.5956, Total Loss: 93370.0312
Epoch[1/15], Step [250/469], Reconst Loss(mse): 93213.7891, KL Div: 431.1582, Total Loss: 93644.9453
Epoch[1/15], Step [300/469], Reconst Loss(mse): 92891.9766, KL Div: 408.7987, Total Loss: 93300.7734
Epoch[1/15], Step [350/469], Reconst Loss(mse): 93079.7188, KL Div: 528.0323, Total Loss: 93607.7500
Epoch[1/15], Step [400/469], Reconst Loss(mse): 92705.6953, KL Div: 317.5992, Total Loss: 93023.2969
Epoch[1/15], Step [450/469], Reconst Loss(mse): 92617.3594, KL Div: 262.1071, Total Loss: 92879.4688
Epoch[2/15], Step [50/469], Reconst Loss(mse): 92652.6406, KL Div: 361.3977, Total Loss: 93014.0391
Epoch[2/15], Step [100/469], Reconst Loss(mse): 92850.9688, KL Div: 325.2642, Total Loss: 93176.2344
Epoch[2/15], Step [150/469], Reconst Loss(mse): 93060.0781, KL Div: 258.3514, Total Loss: 93318.4297
Epoch[2/15], Step [200/469], Reconst Loss(mse): 92561.0469, KL Div: 270.6001, Total Loss: 92831.6484
Epoch[2/15], Step [250/469], Reconst Loss(mse): 92560.8594, KL Div: 303.9872, Total Loss: 92864.8438
Epoch[2/15], Step [300/469], Reconst Loss(mse): 92576.8984, KL Div: 419.0984, Total Loss: 92996.0000
Epoch[2/15], Step [350/469], Reconst Loss(mse): 91831.6562, KL Div: 408.5731, Total Loss: 92240.2266
Epoch[2/15], Step [400/469], Reconst Loss(mse): 91958.3359, KL Div: 423.4749, Total Loss: 92381.8125
Epoch[2/15], Step [450/469], Reconst Loss(mse): 91642.0625, KL Div: 423.4761, Total Loss: 92065.5391
Epoch[3/15], Step [50/469], Reconst Loss(mse): 91604.4609, KL Div: 491.2137, Total Loss: 92095.6719
Epoch[3/15], Step [100/469], Reconst Loss(mse): 91744.7344, KL Div: 520.0927, Total Loss: 92264.8281
Epoch[3/15], Step [150/469], Reconst Loss(mse): 91815.5469, KL Div: 533.6301, Total Loss: 92349.1797
Epoch[3/15], Step [200/469], Reconst Loss(mse): 91569.3438, KL Div: 574.8044, Total Loss: 92144.1484
Epoch[3/15], Step [250/469], Reconst Loss(mse): 91211.2500, KL Div: 630.6614, Total Loss: 91841.9141
Epoch[3/15], Step [300/469], Reconst Loss(mse): 91262.7031, KL Div: 599.9432, Total Loss: 91862.6484
Epoch[3/15], Step [350/469], Reconst Loss(mse): 91236.6406, KL Div: 635.2909, Total Loss: 91871.9297
Epoch[3/15], Step [400/469], Reconst Loss(mse): 91255.2891, KL Div: 682.9257, Total Loss: 91938.2109
Epoch[3/15], Step [450/469], Reconst Loss(mse): 91307.0469, KL Div: 713.5029, Total Loss: 92020.5469
Epoch[4/15], Step [50/469], Reconst Loss(mse): 91153.6875, KL Div: 766.4362, Total Loss: 91920.1250
Epoch[4/15], Step [100/469], Reconst Loss(mse): 91028.3203, KL Div: 748.0986, Total Loss: 91776.4219
Epoch[4/15], Step [150/469], Reconst Loss(mse): 90691.6328, KL Div: 791.9294, Total Loss: 91483.5625
Epoch[4/15], Step [200/469], Reconst Loss(mse): 90676.9766, KL Div: 810.4457, Total Loss: 91487.4219
Epoch[4/15], Step [250/469], Reconst Loss(mse): 91077.3828, KL Div: 805.5142, Total Loss: 91882.8984

Epoch[4/15], Step [300/469], Reconst Loss(mse): 90365.5938, KL Div: 862.2058, Total Loss: 91227.7969
Epoch[4/15], Step [350/469], Reconst Loss(mse): 90598.8281, KL Div: 861.0717, Total Loss: 91459.8984
Epoch[4/15], Step [400/469], Reconst Loss(mse): 90649.3125, KL Div: 902.4860, Total Loss: 91551.7969
Epoch[4/15], Step [450/469], Reconst Loss(mse): 90623.6250, KL Div: 839.0635, Total Loss: 91462.6875
Epoch[5/15], Step [50/469], Reconst Loss(mse): 90295.3125, KL Div: 915.8353, Total Loss: 91211.1484
Epoch[5/15], Step [100/469], Reconst Loss(mse): 90331.1406, KL Div: 993.7852, Total Loss: 91324.9219
Epoch[5/15], Step [150/469], Reconst Loss(mse): 90323.3828, KL Div: 946.2911, Total Loss: 91269.6719
Epoch[5/15], Step [200/469], Reconst Loss(mse): 90547.8516, KL Div: 954.9830, Total Loss: 91502.8359
Epoch[5/15], Step [250/469], Reconst Loss(mse): 90353.8438, KL Div: 993.6180, Total Loss: 91347.4609
Epoch[5/15], Step [300/469], Reconst Loss(mse): 90189.2344, KL Div: 986.1265, Total Loss: 91175.3594
Epoch[5/15], Step [350/469], Reconst Loss(mse): 90291.1562, KL Div: 1035.8479, Total Loss: 91327.0078
Epoch[5/15], Step [400/469], Reconst Loss(mse): 90403.6172, KL Div: 1089.4949, Total Loss: 91493.1094
Epoch[5/15], Step [450/469], Reconst Loss(mse): 89829.1172, KL Div: 1106.7570, Total Loss: 90935.8750
Epoch[6/15], Step [50/469], Reconst Loss(mse): 89675.7891, KL Div: 1096.9615, Total Loss: 90772.7500
Epoch[6/15], Step [100/469], Reconst Loss(mse): 90144.0859, KL Div: 1052.1062, Total Loss: 91196.1953
Epoch[6/15], Step [150/469], Reconst Loss(mse): 90267.8047, KL Div: 1023.0065, Total Loss: 91290.8125
Epoch[6/15], Step [200/469], Reconst Loss(mse): 89966.1562, KL Div: 1072.5544, Total Loss: 91038.7109
Epoch[6/15], Step [250/469], Reconst Loss(mse): 89938.0312, KL Div: 1080.9498, Total Loss: 91018.9844
Epoch[6/15], Step [300/469], Reconst Loss(mse): 90056.6094, KL Div: 1127.4102, Total Loss: 91184.0156
Epoch[6/15], Step [350/469], Reconst Loss(mse): 90579.3438, KL Div: 1094.9822, Total Loss: 91674.3281
Epoch[6/15], Step [400/469], Reconst Loss(mse): 90266.1641, KL Div: 1111.5099, Total Loss: 91377.6719
Epoch[6/15], Step [450/469], Reconst Loss(mse): 90317.0156, KL Div: 1110.5869, Total Loss: 91427.6016
Epoch[7/15], Step [50/469], Reconst Loss(mse): 90217.6484, KL Div: 1092.1613, Total Loss: 91309.8125
Epoch[7/15], Step [100/469], Reconst Loss(mse): 89873.2969, KL Div: 1113.8693, Total Loss: 90987.1641
Epoch[7/15], Step [150/469], Reconst Loss(mse): 89742.0547, KL Div: 1167.9202, Total Loss: 90909.9766
Epoch[7/15], Step [200/469], Reconst Loss(mse): 89791.5859, KL Div: 1123.1815, Total Loss: 90914.7656
Epoch[7/15], Step [250/469], Reconst Loss(mse): 89710.7109, KL Div: 1170.4575, Total Loss: 90881.1719
Epoch[7/15], Step [300/469], Reconst Loss(mse): 89937.4141, KL Div: 1121.7852, Total Loss: 91059.2031
Epoch[7/15], Step [350/469], Reconst Loss(mse): 90154.1719, KL Div: 1103.4484, Total Loss: 91257.6172
Epoch[7/15], Step [400/469], Reconst Loss(mse): 89994.2188, KL Div: 1186.1649, Total Loss: 91180.3828
Epoch[7/15], Step [450/469], Reconst Loss(mse): 89940.7500, KL Div: 1196.1399, Total Loss: 91136.8906
Epoch[8/15], Step [50/469], Reconst Loss(mse): 89707.5000, KL Div: 1172.4875, Total Loss: 90879.9844

Epoch[8/15], Step [100/469], Reconst Loss(mse): 89574.1562, KL Div: 1207.8777, Total Loss: 90782.0312
Epoch[8/15], Step [150/469], Reconst Loss(mse): 89789.5547, KL Div: 1169.3741, Total Loss: 90958.9297
Epoch[8/15], Step [200/469], Reconst Loss(mse): 90254.2031, KL Div: 1152.0947, Total Loss: 91406.2969
Epoch[8/15], Step [250/469], Reconst Loss(mse): 89558.7969, KL Div: 1235.0867, Total Loss: 90793.8828
Epoch[8/15], Step [300/469], Reconst Loss(mse): 89284.9609, KL Div: 1275.5277, Total Loss: 90560.4922
Epoch[8/15], Step [350/469], Reconst Loss(mse): 89963.3281, KL Div: 1236.9083, Total Loss: 91200.2344
Epoch[8/15], Step [400/469], Reconst Loss(mse): 89641.1875, KL Div: 1255.4075, Total Loss: 90896.5938
Epoch[8/15], Step [450/469], Reconst Loss(mse): 90117.8438, KL Div: 1204.3306, Total Loss: 91322.1719
Epoch[9/15], Step [50/469], Reconst Loss(mse): 89489.8438, KL Div: 1252.1633, Total Loss: 90742.0078
Epoch[9/15], Step [100/469], Reconst Loss(mse): 89803.8984, KL Div: 1258.9514, Total Loss: 91062.8516
Epoch[9/15], Step [150/469], Reconst Loss(mse): 89546.0000, KL Div: 1279.2231, Total Loss: 90825.2266
Epoch[9/15], Step [200/469], Reconst Loss(mse): 89614.5312, KL Div: 1276.1564, Total Loss: 90890.6875
Epoch[9/15], Step [250/469], Reconst Loss(mse): 89328.2031, KL Div: 1283.7792, Total Loss: 90611.9844
Epoch[9/15], Step [300/469], Reconst Loss(mse): 89763.1875, KL Div: 1264.3801, Total Loss: 91027.5703
Epoch[9/15], Step [350/469], Reconst Loss(mse): 89636.5156, KL Div: 1297.0112, Total Loss: 90933.5234
Epoch[9/15], Step [400/469], Reconst Loss(mse): 89387.2422, KL Div: 1339.4274, Total Loss: 90726.6719
Epoch[9/15], Step [450/469], Reconst Loss(mse): 89648.1953, KL Div: 1303.2524, Total Loss: 90951.4453
Epoch[10/15], Step [50/469], Reconst Loss(mse): 89185.0312, KL Div: 1407.0155, Total Loss: 90592.0469
Epoch[10/15], Step [100/469], Reconst Loss(mse): 90079.9531, KL Div: 1191.3257, Total Loss: 91271.2812
Epoch[10/15], Step [150/469], Reconst Loss(mse): 89372.4375, KL Div: 1337.1846, Total Loss: 90709.6250
Epoch[10/15], Step [200/469], Reconst Loss(mse): 89202.6406, KL Div: 1367.6073, Total Loss: 90570.2500
Epoch[10/15], Step [250/469], Reconst Loss(mse): 89448.2500, KL Div: 1372.7808, Total Loss: 90821.0312
Epoch[10/15], Step [300/469], Reconst Loss(mse): 89580.4844, KL Div: 1281.7170, Total Loss: 90862.2031
Epoch[10/15], Step [350/469], Reconst Loss(mse): 89271.7109, KL Div: 1344.8645, Total Loss: 90616.5781
Epoch[10/15], Step [400/469], Reconst Loss(mse): 89337.0312, KL Div: 1377.1158, Total Loss: 90714.1484
Epoch[10/15], Step [450/469], Reconst Loss(mse): 89537.5156, KL Div: 1359.5674, Total Loss: 90897.0859
Epoch[11/15], Step [50/469], Reconst Loss(mse): 89321.3359, KL Div: 1299.0128, Total Loss: 90620.3516
Epoch[11/15], Step [100/469], Reconst Loss(mse): 89162.7188, KL Div: 1394.3236, Total Loss: 90557.0391
Epoch[11/15], Step [150/469], Reconst Loss(mse): 89328.6328, KL Div: 1277.6132, Total Loss: 90606.2422
Epoch[11/15], Step [200/469], Reconst Loss(mse): 89488.0703, KL Div: 1370.6796, Total Loss: 90858.7500
Epoch[11/15], Step [250/469], Reconst Loss(mse): 89330.0078, KL Div: 1417.5770, Total Loss: 90747.5859
Epoch[11/15], Step [300/469], Reconst Loss(mse): 89358.8438, KL Div: 1353.1584, Total Loss: 90712.0000

Epoch[11/15], Step [350/469], Reconst Loss(mse): 89350.4922, KL Div: 1346.9744, Tota
l Loss: 90697.4688
Epoch[11/15], Step [400/469], Reconst Loss(mse): 89649.4062, KL Div: 1347.2731, Tota
l Loss: 90996.6797
Epoch[11/15], Step [450/469], Reconst Loss(mse): 89403.5625, KL Div: 1395.3208, Tota
l Loss: 90798.8828
Epoch[12/15], Step [50/469], Reconst Loss(mse): 89358.7266, KL Div: 1388.3865, Total
Loss: 90747.1094
Epoch[12/15], Step [100/469], Reconst Loss(mse): 89047.0859, KL Div: 1347.8242, Tota
l Loss: 90394.9062
Epoch[12/15], Step [150/469], Reconst Loss(mse): 89275.8828, KL Div: 1383.5154, Tota
l Loss: 90659.3984
Epoch[12/15], Step [200/469], Reconst Loss(mse): 89104.3438, KL Div: 1394.7500, Tota
l Loss: 90499.0938
Epoch[12/15], Step [250/469], Reconst Loss(mse): 89277.5781, KL Div: 1290.1514, Tota
l Loss: 90567.7266
Epoch[12/15], Step [300/469], Reconst Loss(mse): 89620.9531, KL Div: 1345.6106, Tota
l Loss: 90966.5625
Epoch[12/15], Step [350/469], Reconst Loss(mse): 89641.8672, KL Div: 1398.3896, Tota
l Loss: 91040.2578
Epoch[12/15], Step [400/469], Reconst Loss(mse): 89487.7188, KL Div: 1342.2390, Tota
l Loss: 90829.9609
Epoch[12/15], Step [450/469], Reconst Loss(mse): 89329.9844, KL Div: 1374.3574, Tota
l Loss: 90704.3438
Epoch[13/15], Step [50/469], Reconst Loss(mse): 89146.0000, KL Div: 1435.0173, Total
Loss: 90581.0156
Epoch[13/15], Step [100/469], Reconst Loss(mse): 89351.0469, KL Div: 1387.8817, Tota
l Loss: 90738.9297
Epoch[13/15], Step [150/469], Reconst Loss(mse): 89467.5312, KL Div: 1440.6090, Tota
l Loss: 90908.1406
Epoch[13/15], Step [200/469], Reconst Loss(mse): 89782.2500, KL Div: 1380.4473, Tota
l Loss: 91162.6953
Epoch[13/15], Step [250/469], Reconst Loss(mse): 88991.8672, KL Div: 1471.8734, Tota
l Loss: 90463.7422
Epoch[13/15], Step [300/469], Reconst Loss(mse): 88799.8594, KL Div: 1500.3914, Tota
l Loss: 90300.2500
Epoch[13/15], Step [350/469], Reconst Loss(mse): 89285.8125, KL Div: 1415.0309, Tota
l Loss: 90700.8438
Epoch[13/15], Step [400/469], Reconst Loss(mse): 89305.6797, KL Div: 1397.1429, Tota
l Loss: 90702.8203
Epoch[13/15], Step [450/469], Reconst Loss(mse): 89351.7734, KL Div: 1413.6962, Tota
l Loss: 90765.4688
Epoch[14/15], Step [50/469], Reconst Loss(mse): 89407.7344, KL Div: 1421.0836, Total
Loss: 90828.8203
Epoch[14/15], Step [100/469], Reconst Loss(mse): 89635.0391, KL Div: 1364.1371, Tota
l Loss: 90999.1797
Epoch[14/15], Step [150/469], Reconst Loss(mse): 89337.2734, KL Div: 1417.9202, Tota
l Loss: 90755.1953
Epoch[14/15], Step [200/469], Reconst Loss(mse): 88915.5938, KL Div: 1471.0724, Tota
l Loss: 90386.6641
Epoch[14/15], Step [250/469], Reconst Loss(mse): 88901.3984, KL Div: 1485.4604, Tota
l Loss: 90386.8594
Epoch[14/15], Step [300/469], Reconst Loss(mse): 89276.7109, KL Div: 1488.8123, Tota
l Loss: 90765.5234
Epoch[14/15], Step [350/469], Reconst Loss(mse): 88919.7969, KL Div: 1488.2001, Tota
l Loss: 90408.0000
Epoch[14/15], Step [400/469], Reconst Loss(mse): 88588.3906, KL Div: 1563.6010, Tota
l Loss: 90151.9922
Epoch[14/15], Step [450/469], Reconst Loss(mse): 88978.1250, KL Div: 1485.3595, Tota
l Loss: 90463.4844
Epoch[15/15], Step [50/469], Reconst Loss(mse): 89027.7969, KL Div: 1458.0155, Total
Loss: 90485.8125
Epoch[15/15], Step [100/469], Reconst Loss(mse): 89506.1562, KL Div: 1405.5134, Tota
l Loss: 90911.6719

```
Epoch[15/15], Step [150/469], Reconst Loss(mse): 89233.8984, KL Div: 1401.8114, Tota
l Loss: 90635.7109
Epoch[15/15], Step [200/469], Reconst Loss(mse): 88873.9375, KL Div: 1483.7257, Tota
l Loss: 90357.6641
Epoch[15/15], Step [250/469], Reconst Loss(mse): 88985.3516, KL Div: 1469.1841, Tota
l Loss: 90454.5391
Epoch[15/15], Step [300/469], Reconst Loss(mse): 89443.8438, KL Div: 1444.6899, Tota
l Loss: 90888.5312
Epoch[15/15], Step [350/469], Reconst Loss(mse): 89118.9219, KL Div: 1432.1404, Tota
l Loss: 90551.0625
Epoch[15/15], Step [400/469], Reconst Loss(mse): 89086.3750, KL Div: 1511.4711, Tota
l Loss: 90597.8438
Epoch[15/15], Step [450/469], Reconst Loss(mse): 89187.1875, KL Div: 1512.4517, Tota
l Loss: 90699.6406
```

添加mask

为了添加mask，我们在输入图像的中央区域创建一个掩码，并使用该掩码将图像的中心区域替换为全零张量。然后，我们将这个掩码与输入图像进行按位或运算，从而得到一个新的输入图像。

具体到代码实现，我们需要重写VAE类，在VAE的init函数中定义mask，以便实例化时一起初始化。

在VAE类的forward函数中使用mask进行运算。在解码隐变量z之前，使用mask与隐变量z进行按位或运算，从而创建新的隐变量z'。接下来，使用z'替换z，并使用z'解码为重构值x'。最后，使用x'计算 VAE 的损失函数。

In [16]:
```python
class VAE_mask(nn.Module):
    def __init__(self, image_size=784, h_dim=400, z_dim=20):
        super(VAE_mask, self).__init__()
        self.fc1 = nn.Linear(image_size, h_dim)
        self.fc2 = nn.Linear(h_dim, z_dim)
        self.fc3 = nn.Linear(h_dim, z_dim)
        self.fc4 = nn.Linear(z_dim, h_dim)
        self.fc5 = nn.Linear(h_dim, image_size)

        #定义掩码
        self.mask = torch.zeros(1, z_dim, dtype=torch.float)
        self.mask[:, :10] = 1.0

    def encode(self, x):
        h = F.relu(self.fc1(x))
        return self.fc2(h), self.fc3(h)

    def reparameterize(self, mu, log_var):
        std = torch.exp(log_var / 2)
        eps = torch.randn_like(std)
        return mu + eps * std

    def decode(self, z):
        h = F.relu(self.fc4(z))
        return F.sigmoid(self.fc5(h))

    def forward(self, x):
        mu, log_var = self.encode(x)
        z = self.reparameterize(mu, log_var)
        #使用mask得到新的隐变量z'
        z = z * self.mask * 100
        x_reconst = self.decode(z)
        return x_reconst, mu, log_var
```

```python
#创建新目录保存结果
sample_dir_mse_mask = 'advanced/modified dataset/samples_mse_mask'
if not os.path.exists(sample_dir_mse_mask):
    os.makedirs(sample_dir_mse_mask)

#使用带有mask的VAE类
model_mask = VAE_mask().to(device)

optimizer = torch.optim.Adam(model_mask.parameters(), lr=learning_rate)

beta = 1.0

for epoch in range(num_epochs):
    for i, (x, _) in enumerate(data_loader):
        x = x.to(device).view(-1,image_size)
        #使用带有mask的model
        x_reconst, mu, log_var = model_mask(x)

        reconst_loss = F.mse_loss(x_reconst, x, size_average=False)

        kl_div = - 0.5 * torch.sum(1 + log_var - mu.pow(2) - log_var.exp())
        kl_div = beta * kl_div

        loss = reconst_loss + kl_div

        optimizer.zero_grad()

        loss.backward()

        optimizer.step()

        if (i + 1) % 50 == 0:
            print("Epoch[{}/{}], Step [{}/{}], Reconst Loss(mse): {:.4f}, KL Div: {:
                  .format(epoch + 1, num_epochs, i + 1, len(data_loader), reconst_lo

    with torch.no_grad():
        # 改变保存路径
        z = torch.randn(batch_size, z_dim).to(device)
        out = model.decode(z).view(-1, 1, 28, 28)
        save_image(out, os.path.join(sample_dir_mse_mask, 'sampled-{}.png'.format(ep
        out, _, _ = model(x)
        x_concat = torch.cat([x.view(-1, 1, 28, 28), out.view(-1, 1, 28, 28)], dim=
        save_image(x_concat, os.path.join(sample_dir_mse_mask, 'reconst-{}.png'.form
```

```
Epoch[1/15], Step [50/469], Reconst Loss(mse): 10493.5264, KL Div: 178.6552, Total L
oss: 10672.1816
Epoch[1/15], Step [100/469], Reconst Loss(mse): 9772.5898, KL Div: 415.7194, Total L
oss: 10188.3096
Epoch[1/15], Step [150/469], Reconst Loss(mse): 9779.2715, KL Div: 457.2917, Total L
oss: 10236.5635
Epoch[1/15], Step [200/469], Reconst Loss(mse): 9312.2783, KL Div: 537.2988, Total L
oss: 9849.5771
Epoch[1/15], Step [250/469], Reconst Loss(mse): 9348.5742, KL Div: 643.9611, Total L
oss: 9992.5352
Epoch[1/15], Step [300/469], Reconst Loss(mse): 9596.4463, KL Div: 682.2031, Total L
oss: 10278.6494
Epoch[1/15], Step [350/469], Reconst Loss(mse): 8738.9092, KL Div: 649.4675, Total L
oss: 9388.3770
Epoch[1/15], Step [400/469], Reconst Loss(mse): 8543.0957, KL Div: 736.7505, Total L
oss: 9279.8457
Epoch[1/15], Step [450/469], Reconst Loss(mse): 9172.5273, KL Div: 770.6074, Total L
oss: 9943.1348
Epoch[2/15], Step [50/469], Reconst Loss(mse): 8370.0693, KL Div: 780.9128, Total Lo
ss: 9150.9824
Epoch[2/15], Step [100/469], Reconst Loss(mse): 8097.3564, KL Div: 814.0497, Total L
oss: 8911.4062
Epoch[2/15], Step [150/469], Reconst Loss(mse): 7921.2744, KL Div: 885.1666, Total L
oss: 8806.4414
Epoch[2/15], Step [200/469], Reconst Loss(mse): 8212.1572, KL Div: 852.6879, Total L
oss: 9064.8447
Epoch[2/15], Step [250/469], Reconst Loss(mse): 8589.4990, KL Div: 793.5312, Total L
oss: 9383.0303
Epoch[2/15], Step [300/469], Reconst Loss(mse): 8524.0732, KL Div: 844.2209, Total L
oss: 9368.2939
Epoch[2/15], Step [350/469], Reconst Loss(mse): 7755.7646, KL Div: 894.5212, Total L
oss: 8650.2861
Epoch[2/15], Step [400/469], Reconst Loss(mse): 8066.9492, KL Div: 892.5095, Total L
oss: 8959.4590
Epoch[2/15], Step [450/469], Reconst Loss(mse): 8033.6445, KL Div: 876.2737, Total L
oss: 8909.9180
Epoch[3/15], Step [50/469], Reconst Loss(mse): 8285.5498, KL Div: 911.0199, Total Lo
ss: 9196.5693
Epoch[3/15], Step [100/469], Reconst Loss(mse): 8109.3403, KL Div: 928.0112, Total L
oss: 9037.3516
Epoch[3/15], Step [150/469], Reconst Loss(mse): 7801.8350, KL Div: 952.3878, Total L
oss: 8754.2227
Epoch[3/15], Step [200/469], Reconst Loss(mse): 8342.2412, KL Div: 963.7446, Total L
oss: 9305.9863
Epoch[3/15], Step [250/469], Reconst Loss(mse): 8017.7471, KL Div: 938.2517, Total L
oss: 8955.9990
Epoch[3/15], Step [300/469], Reconst Loss(mse): 8031.4141, KL Div: 904.2334, Total L
oss: 8935.6475
Epoch[3/15], Step [350/469], Reconst Loss(mse): 7806.9556, KL Div: 964.6053, Total L
oss: 8771.5605
Epoch[3/15], Step [400/469], Reconst Loss(mse): 7466.6211, KL Div: 963.8899, Total L
oss: 8430.5107
Epoch[3/15], Step [450/469], Reconst Loss(mse): 8032.2656, KL Div: 992.8375, Total L
oss: 9025.1035
Epoch[4/15], Step [50/469], Reconst Loss(mse): 7636.0615, KL Div: 922.6661, Total Lo
ss: 8558.7275
Epoch[4/15], Step [100/469], Reconst Loss(mse): 7516.2988, KL Div: 966.6683, Total L
oss: 8482.9668
Epoch[4/15], Step [150/469], Reconst Loss(mse): 7473.7026, KL Div: 956.2434, Total L
oss: 8429.9463
Epoch[4/15], Step [200/469], Reconst Loss(mse): 7746.6611, KL Div: 1010.3464, Total
Loss: 8757.0078
Epoch[4/15], Step [250/469], Reconst Loss(mse): 7760.0811, KL Div: 962.2047, Total L
oss: 8722.2861
```

Epoch[4/15], Step [300/469], Reconst Loss(mse): 8026.5117, KL Div: 976.3066, Total Loss: 9002.8184
Epoch[4/15], Step [350/469], Reconst Loss(mse): 7362.6895, KL Div: 977.3285, Total Loss: 8340.0176
Epoch[4/15], Step [400/469], Reconst Loss(mse): 7511.5557, KL Div: 995.5253, Total Loss: 8507.0811
Epoch[4/15], Step [450/469], Reconst Loss(mse): 7594.1162, KL Div: 1018.8665, Total Loss: 8612.9824
Epoch[5/15], Step [50/469], Reconst Loss(mse): 7319.2725, KL Div: 1043.8829, Total Loss: 8363.1553
Epoch[5/15], Step [100/469], Reconst Loss(mse): 6973.8838, KL Div: 1030.1902, Total Loss: 8004.0742
Epoch[5/15], Step [150/469], Reconst Loss(mse): 7716.1230, KL Div: 1084.4070, Total Loss: 8800.5303
Epoch[5/15], Step [200/469], Reconst Loss(mse): 7675.7520, KL Div: 1141.4282, Total Loss: 8817.1797
Epoch[5/15], Step [250/469], Reconst Loss(mse): 6773.8975, KL Div: 1064.2692, Total Loss: 7838.1665
Epoch[5/15], Step [300/469], Reconst Loss(mse): 6880.1284, KL Div: 1124.0602, Total Loss: 8004.1885
Epoch[5/15], Step [350/469], Reconst Loss(mse): 6662.0273, KL Div: 1173.6735, Total Loss: 7835.7007
Epoch[5/15], Step [400/469], Reconst Loss(mse): 6822.4980, KL Div: 1157.6488, Total Loss: 7980.1470
Epoch[5/15], Step [450/469], Reconst Loss(mse): 6022.8828, KL Div: 1156.7277, Total Loss: 7179.6104
Epoch[6/15], Step [50/469], Reconst Loss(mse): 4627.3350, KL Div: 1496.0708, Total Loss: 6123.4058
Epoch[6/15], Step [100/469], Reconst Loss(mse): 4090.3223, KL Div: 1469.2311, Total Loss: 5559.5532
Epoch[6/15], Step [150/469], Reconst Loss(mse): 3506.1348, KL Div: 1455.6417, Total Loss: 4961.7764
Epoch[6/15], Step [200/469], Reconst Loss(mse): 3363.2349, KL Div: 1461.9631, Total Loss: 4825.1982
Epoch[6/15], Step [250/469], Reconst Loss(mse): 3244.2261, KL Div: 1394.6565, Total Loss: 4638.8828
Epoch[6/15], Step [300/469], Reconst Loss(mse): 3292.6997, KL Div: 1489.2629, Total Loss: 4781.9629
Epoch[6/15], Step [350/469], Reconst Loss(mse): 3069.2131, KL Div: 1447.6191, Total Loss: 4516.8320
Epoch[6/15], Step [400/469], Reconst Loss(mse): 3006.8176, KL Div: 1464.9532, Total Loss: 4471.7710
Epoch[6/15], Step [450/469], Reconst Loss(mse): 3154.3816, KL Div: 1432.0540, Total Loss: 4586.4355
Epoch[7/15], Step [50/469], Reconst Loss(mse): 3029.9316, KL Div: 1489.7715, Total Loss: 4519.7031
Epoch[7/15], Step [100/469], Reconst Loss(mse): 2929.7661, KL Div: 1393.9724, Total Loss: 4323.7383
Epoch[7/15], Step [150/469], Reconst Loss(mse): 2725.4639, KL Div: 1447.2372, Total Loss: 4172.7012
Epoch[7/15], Step [200/469], Reconst Loss(mse): 2963.6902, KL Div: 1458.2195, Total Loss: 4421.9097
Epoch[7/15], Step [250/469], Reconst Loss(mse): 2714.8840, KL Div: 1464.3685, Total Loss: 4179.2524
Epoch[7/15], Step [300/469], Reconst Loss(mse): 2876.5259, KL Div: 1439.6670, Total Loss: 4316.1929
Epoch[7/15], Step [350/469], Reconst Loss(mse): 2676.7036, KL Div: 1469.1714, Total Loss: 4145.8750
Epoch[7/15], Step [400/469], Reconst Loss(mse): 2828.2734, KL Div: 1463.5087, Total Loss: 4291.7822
Epoch[7/15], Step [450/469], Reconst Loss(mse): 3014.9548, KL Div: 1425.8882, Total Loss: 4440.8428
Epoch[8/15], Step [50/469], Reconst Loss(mse): 2716.0337, KL Div: 1419.4355, Total Loss: 4135.4692

Epoch[8/15], Step [100/469], Reconst Loss(mse): 2680.3120, KL Div: 1446.1996, Total Loss: 4126.5117
Epoch[8/15], Step [150/469], Reconst Loss(mse): 2889.9961, KL Div: 1438.0854, Total Loss: 4328.0815
Epoch[8/15], Step [200/469], Reconst Loss(mse): 2549.8887, KL Div: 1502.8857, Total Loss: 4052.7744
Epoch[8/15], Step [250/469], Reconst Loss(mse): 2950.8479, KL Div: 1401.6064, Total Loss: 4352.4541
Epoch[8/15], Step [300/469], Reconst Loss(mse): 2814.5408, KL Div: 1417.8602, Total Loss: 4232.4009
Epoch[8/15], Step [350/469], Reconst Loss(mse): 2730.4331, KL Div: 1429.7445, Total Loss: 4160.1777
Epoch[8/15], Step [400/469], Reconst Loss(mse): 2723.8799, KL Div: 1487.7371, Total Loss: 4211.6172
Epoch[8/15], Step [450/469], Reconst Loss(mse): 2655.5508, KL Div: 1424.1675, Total Loss: 4079.7183
Epoch[9/15], Step [50/469], Reconst Loss(mse): 2670.2798, KL Div: 1450.8861, Total Loss: 4121.1660
Epoch[9/15], Step [100/469], Reconst Loss(mse): 2668.6699, KL Div: 1468.5221, Total Loss: 4137.1919
Epoch[9/15], Step [150/469], Reconst Loss(mse): 2507.7397, KL Div: 1498.2947, Total Loss: 4006.0344
Epoch[9/15], Step [200/469], Reconst Loss(mse): 2631.2788, KL Div: 1485.6327, Total Loss: 4116.9116
Epoch[9/15], Step [250/469], Reconst Loss(mse): 2558.4258, KL Div: 1491.8490, Total Loss: 4050.2749
Epoch[9/15], Step [300/469], Reconst Loss(mse): 2591.2041, KL Div: 1492.9435, Total Loss: 4084.1475
Epoch[9/15], Step [350/469], Reconst Loss(mse): 2689.8035, KL Div: 1463.1732, Total Loss: 4152.9766
Epoch[9/15], Step [400/469], Reconst Loss(mse): 2671.7141, KL Div: 1465.6051, Total Loss: 4137.3193
Epoch[9/15], Step [450/469], Reconst Loss(mse): 2533.5115, KL Div: 1414.5403, Total Loss: 3948.0518
Epoch[10/15], Step [50/469], Reconst Loss(mse): 2654.5186, KL Div: 1463.7498, Total Loss: 4118.2686
Epoch[10/15], Step [100/469], Reconst Loss(mse): 2515.6973, KL Div: 1455.1774, Total Loss: 3970.8745
Epoch[10/15], Step [150/469], Reconst Loss(mse): 2573.7534, KL Div: 1478.9410, Total Loss: 4052.6943
Epoch[10/15], Step [200/469], Reconst Loss(mse): 2449.2534, KL Div: 1481.2043, Total Loss: 3930.4578
Epoch[10/15], Step [250/469], Reconst Loss(mse): 2780.3672, KL Div: 1463.9615, Total Loss: 4244.3286
Epoch[10/15], Step [300/469], Reconst Loss(mse): 2578.9575, KL Div: 1454.8113, Total Loss: 4033.7688
Epoch[10/15], Step [350/469], Reconst Loss(mse): 2645.0176, KL Div: 1493.0812, Total Loss: 4138.0986
Epoch[10/15], Step [400/469], Reconst Loss(mse): 2641.0288, KL Div: 1461.8406, Total Loss: 4102.8691
Epoch[10/15], Step [450/469], Reconst Loss(mse): 2720.0396, KL Div: 1455.1196, Total Loss: 4175.1592
Epoch[11/15], Step [50/469], Reconst Loss(mse): 2588.2798, KL Div: 1463.2787, Total Loss: 4051.5586
Epoch[11/15], Step [100/469], Reconst Loss(mse): 2560.9431, KL Div: 1509.6233, Total Loss: 4070.5664
Epoch[11/15], Step [150/469], Reconst Loss(mse): 2713.3750, KL Div: 1442.8826, Total Loss: 4156.2578
Epoch[11/15], Step [200/469], Reconst Loss(mse): 2613.0618, KL Div: 1495.2017, Total Loss: 4108.2637
Epoch[11/15], Step [250/469], Reconst Loss(mse): 2748.0786, KL Div: 1519.4431, Total Loss: 4267.5215
Epoch[11/15], Step [300/469], Reconst Loss(mse): 2656.5645, KL Div: 1512.5692, Total Loss: 4169.1338

Epoch[11/15], Step [350/469], Reconst Loss(mse): 2594.9490, KL Div: 1484.6891, Total Loss: 4079.6382
Epoch[11/15], Step [400/469], Reconst Loss(mse): 2436.7898, KL Div: 1483.1615, Total Loss: 3919.9512
Epoch[11/15], Step [450/469], Reconst Loss(mse): 2450.3750, KL Div: 1431.8347, Total Loss: 3882.2097
Epoch[12/15], Step [50/469], Reconst Loss(mse): 2603.7964, KL Div: 1495.6167, Total Loss: 4099.4131
Epoch[12/15], Step [100/469], Reconst Loss(mse): 2464.4756, KL Div: 1433.1455, Total Loss: 3897.6211
Epoch[12/15], Step [150/469], Reconst Loss(mse): 2640.5232, KL Div: 1548.4470, Total Loss: 4188.9702
Epoch[12/15], Step [200/469], Reconst Loss(mse): 2512.4326, KL Div: 1487.8009, Total Loss: 4000.2334
Epoch[12/15], Step [250/469], Reconst Loss(mse): 2620.2598, KL Div: 1478.9453, Total Loss: 4099.2051
Epoch[12/15], Step [300/469], Reconst Loss(mse): 2430.1428, KL Div: 1464.5624, Total Loss: 3894.7051
Epoch[12/15], Step [350/469], Reconst Loss(mse): 2650.4636, KL Div: 1444.4788, Total Loss: 4094.9424
Epoch[12/15], Step [400/469], Reconst Loss(mse): 2742.2573, KL Div: 1554.8624, Total Loss: 4297.1196
Epoch[12/15], Step [450/469], Reconst Loss(mse): 2619.1506, KL Div: 1453.9479, Total Loss: 4073.0986
Epoch[13/15], Step [50/469], Reconst Loss(mse): 2605.8584, KL Div: 1492.1692, Total Loss: 4098.0273
Epoch[13/15], Step [100/469], Reconst Loss(mse): 2612.8909, KL Div: 1436.4966, Total Loss: 4049.3875
Epoch[13/15], Step [150/469], Reconst Loss(mse): 2548.6855, KL Div: 1453.4666, Total Loss: 4002.1521
Epoch[13/15], Step [200/469], Reconst Loss(mse): 2530.3945, KL Div: 1473.6536, Total Loss: 4004.0481
Epoch[13/15], Step [250/469], Reconst Loss(mse): 2672.3569, KL Div: 1497.1709, Total Loss: 4169.5278
Epoch[13/15], Step [300/469], Reconst Loss(mse): 2577.9509, KL Div: 1456.8531, Total Loss: 4034.8042
Epoch[13/15], Step [350/469], Reconst Loss(mse): 2596.9116, KL Div: 1508.0844, Total Loss: 4104.9961
Epoch[13/15], Step [400/469], Reconst Loss(mse): 2545.9624, KL Div: 1503.6179, Total Loss: 4049.5803
Epoch[13/15], Step [450/469], Reconst Loss(mse): 2435.9331, KL Div: 1501.5238, Total Loss: 3937.4570
Epoch[14/15], Step [50/469], Reconst Loss(mse): 2549.2954, KL Div: 1480.5762, Total Loss: 4029.8716
Epoch[14/15], Step [100/469], Reconst Loss(mse): 2543.3210, KL Div: 1509.6014, Total Loss: 4052.9224
Epoch[14/15], Step [150/469], Reconst Loss(mse): 2574.2368, KL Div: 1531.5328, Total Loss: 4105.7695
Epoch[14/15], Step [200/469], Reconst Loss(mse): 2469.8809, KL Div: 1478.1823, Total Loss: 3948.0630
Epoch[14/15], Step [250/469], Reconst Loss(mse): 2341.8496, KL Div: 1517.2969, Total Loss: 3859.1465
Epoch[14/15], Step [300/469], Reconst Loss(mse): 2416.4595, KL Div: 1534.1337, Total Loss: 3950.5933
Epoch[14/15], Step [350/469], Reconst Loss(mse): 2335.8110, KL Div: 1515.0735, Total Loss: 3850.8845
Epoch[14/15], Step [400/469], Reconst Loss(mse): 2443.7273, KL Div: 1475.6316, Total Loss: 3919.3589
Epoch[14/15], Step [450/469], Reconst Loss(mse): 2442.4956, KL Div: 1461.2738, Total Loss: 3903.7695
Epoch[15/15], Step [50/469], Reconst Loss(mse): 2601.5627, KL Div: 1494.8035, Total Loss: 4096.3662
Epoch[15/15], Step [100/469], Reconst Loss(mse): 2524.0046, KL Div: 1435.3295, Total Loss: 3959.3340

```
Epoch[15/15], Step [150/469], Reconst Loss(mse): 2559.3901, KL Div: 1525.8191, Total
Loss: 4085.2092
Epoch[15/15], Step [200/469], Reconst Loss(mse): 2399.3101, KL Div: 1473.0190, Total
Loss: 3872.3291
Epoch[15/15], Step [250/469], Reconst Loss(mse): 2545.3254, KL Div: 1455.8579, Total
Loss: 4001.1833
Epoch[15/15], Step [300/469], Reconst Loss(mse): 2312.8560, KL Div: 1550.7662, Total
Loss: 3863.6221
Epoch[15/15], Step [350/469], Reconst Loss(mse): 2574.1763, KL Div: 1433.2556, Total
Loss: 4007.4319
Epoch[15/15], Step [400/469], Reconst Loss(mse): 2534.0112, KL Div: 1451.2563, Total
Loss: 3985.2676
Epoch[15/15], Step [450/469], Reconst Loss(mse): 2492.0007, KL Div: 1439.5540, Total
Loss: 3931.5547
```

提高要求3：对可视化方法进行创新

对隐变量z进行输出。使用t-SNE算法将z降维到二维，然后使用散点图可视化z。 为了可视化
输出z，我们需要重写VAE类，返回隐变量z。

In [17]:
```python
class VAE_returnz(nn.Module):
    def __init__(self, image_size=784, h_dim=400, z_dim=20):
        super(VAE_returnz, self).__init__()
        self.fc1 = nn.Linear(image_size, h_dim)
        self.fc2 = nn.Linear(h_dim, z_dim)
        self.fc3 = nn.Linear(h_dim, z_dim)
        self.fc4 = nn.Linear(z_dim, h_dim)
        self.fc5 = nn.Linear(h_dim, image_size)

    def encode(self, x):
        h = F.relu(self.fc1(x))
        return self.fc2(h), self.fc3(h)

    def reparameterize(self, mu, log_var):
        std = torch.exp(log_var / 2)
        eps = torch.randn_like(std)
        return mu + eps * std

    def decode(self, z):
        h = F.relu(self.fc4(z))
        return F.sigmoid(self.fc5(h))

    def forward(self, x):
        mu, log_var = self.encode(x)
        z = self.reparameterize(mu, log_var)
        x_reconst = self.decode(z)
        #返回z
        return x_reconst, mu, log_var, z


#使用返回z的VAE类
model_returnz = VAE_returnz().to(device)

optimizer = torch.optim.Adam(model_returnz.parameters(), lr=learning_rate)

beta = 1.0

for epoch in range(num_epochs):
    for i, (x, _) in enumerate(data_loader):
        x = x.to(device).view(-1,image_size)
        #使用返回z的model
        x_reconst, mu, log_var, returnz = model_returnz(x)
```

```python
            reconst_loss = F.mse_loss(x_reconst, x, size_average=False)

            kl_div = - 0.5 * torch.sum(1 + log_var - mu.pow(2) - log_var.exp())
            kl_div = beta * kl_div

            loss = reconst_loss + kl_div

            optimizer.zero_grad()

            loss.backward()

            optimizer.step()

            if (i + 1) % 50 == 0:
                print("Epoch[{}/{}], Step [{}/{}], Reconst Loss(ce): {:.4f}, KL Div: {:.
                      .format(epoch + 1, num_epochs, i + 1, len(data_loader), reconst_lo

            if (epoch==num_epochs-1 and i==len(data_loader)-1):
                from sklearn.manifold import TSNE
                import matplotlib.pyplot as plt

                # 将隐变量 z 投射到二维平面
                z_embedded = TSNE(n_components=2).fit_transform(returnz.detach().numpy()

                # 可视化隐变量
                plt.scatter(z_embedded[:, 0], z_embedded[:, 1])
                plt.show()
```

Epoch[1/15], Step [50/469], Reconst Loss(ce): 6871.3501, KL Div: 163.4820, Total Loss: 7034.8320

Epoch[1/15], Step [100/469], Reconst Loss(ce): 6022.7070, KL Div: 323.4783, Total Loss: 6346.1855

Epoch[1/15], Step [150/469], Reconst Loss(ce): 5133.9048, KL Div: 610.7886, Total Loss: 5744.6934

Epoch[1/15], Step [200/469], Reconst Loss(ce): 4841.2222, KL Div: 742.7969, Total Loss: 5584.0190

Epoch[1/15], Step [250/469], Reconst Loss(ce): 4525.0947, KL Div: 864.1104, Total Loss: 5389.2051

Epoch[1/15], Step [300/469], Reconst Loss(ce): 4404.1494, KL Div: 973.2102, Total Loss: 5377.3594

Epoch[1/15], Step [350/469], Reconst Loss(ce): 4088.4209, KL Div: 958.9673, Total Loss: 5047.3882

Epoch[1/15], Step [400/469], Reconst Loss(ce): 3949.4797, KL Div: 1073.9836, Total Loss: 5023.4634

Epoch[1/15], Step [450/469], Reconst Loss(ce): 3637.5469, KL Div: 1128.6135, Total Loss: 4766.1602

Epoch[2/15], Step [50/469], Reconst Loss(ce): 3427.3787, KL Div: 1173.3159, Total Loss: 4600.6943

Epoch[2/15], Step [100/469], Reconst Loss(ce): 3187.2646, KL Div: 1313.8669, Total Loss: 4501.1318

Epoch[2/15], Step [150/469], Reconst Loss(ce): 3337.9468, KL Div: 1230.9209, Total Loss: 4568.8677

Epoch[2/15], Step [200/469], Reconst Loss(ce): 3242.5500, KL Div: 1208.3389, Total Loss: 4450.8887

Epoch[2/15], Step [250/469], Reconst Loss(ce): 3047.4231, KL Div: 1265.9781, Total Loss: 4313.4014

Epoch[2/15], Step [300/469], Reconst Loss(ce): 3006.1084, KL Div: 1367.9756, Total Loss: 4374.0840

Epoch[2/15], Step [350/469], Reconst Loss(ce): 3121.3977, KL Div: 1324.4005, Total Loss: 4445.7983

Epoch[2/15], Step [400/469], Reconst Loss(ce): 3004.8743, KL Div: 1304.0366, Total Loss: 4308.9111

Epoch[2/15], Step [450/469], Reconst Loss(ce): 2967.3074, KL Div: 1413.4596, Total Loss: 4380.7671

Epoch[3/15], Step [50/469], Reconst Loss(ce): 3037.0027, KL Div: 1359.3765, Total Loss: 4396.3789

Epoch[3/15], Step [100/469], Reconst Loss(ce): 2803.1997, KL Div: 1422.8882, Total Loss: 4226.0879

Epoch[3/15], Step [150/469], Reconst Loss(ce): 2873.2661, KL Div: 1380.3585, Total Loss: 4253.6245

Epoch[3/15], Step [200/469], Reconst Loss(ce): 2754.9939, KL Div: 1382.5609, Total Loss: 4137.5547

Epoch[3/15], Step [250/469], Reconst Loss(ce): 2953.7144, KL Div: 1406.6464, Total Loss: 4360.3608

Epoch[3/15], Step [300/469], Reconst Loss(ce): 2785.1152, KL Div: 1377.5356, Total Loss: 4162.6509

Epoch[3/15], Step [350/469], Reconst Loss(ce): 2789.6560, KL Div: 1442.9862, Total Loss: 4232.6421

Epoch[3/15], Step [400/469], Reconst Loss(ce): 2882.3540, KL Div: 1480.9683, Total Loss: 4363.3223

Epoch[3/15], Step [450/469], Reconst Loss(ce): 2722.3105, KL Div: 1439.0139, Total Loss: 4161.3242

Epoch[4/15], Step [50/469], Reconst Loss(ce): 2676.9895, KL Div: 1412.1642, Total Loss: 4089.1538

Epoch[4/15], Step [100/469], Reconst Loss(ce): 2750.9209, KL Div: 1486.7244, Total Loss: 4237.6455

Epoch[4/15], Step [150/469], Reconst Loss(ce): 2479.7205, KL Div: 1400.1564, Total Loss: 3879.8770

Epoch[4/15], Step [200/469], Reconst Loss(ce): 2886.9663, KL Div: 1375.2794, Total Loss: 4262.2456

Epoch[4/15], Step [250/469], Reconst Loss(ce): 2607.6323, KL Div: 1507.5967, Total Loss: 4115.2290

Epoch[4/15], Step [300/469], Reconst Loss(ce): 2619.2908, KL Div: 1440.9564, Total Loss: 4060.2471
Epoch[4/15], Step [350/469], Reconst Loss(ce): 2852.8694, KL Div: 1478.2518, Total Loss: 4331.1211
Epoch[4/15], Step [400/469], Reconst Loss(ce): 2603.8772, KL Div: 1461.7971, Total Loss: 4065.6743
Epoch[4/15], Step [450/469], Reconst Loss(ce): 2368.5767, KL Div: 1506.1917, Total Loss: 3874.7683
Epoch[5/15], Step [50/469], Reconst Loss(ce): 2633.7332, KL Div: 1485.5244, Total Loss: 4119.2578
Epoch[5/15], Step [100/469], Reconst Loss(ce): 2466.2517, KL Div: 1485.1417, Total Loss: 3951.3936
Epoch[5/15], Step [150/469], Reconst Loss(ce): 2433.6826, KL Div: 1540.0811, Total Loss: 3973.7637
Epoch[5/15], Step [200/469], Reconst Loss(ce): 2518.4644, KL Div: 1445.9878, Total Loss: 3964.4521
Epoch[5/15], Step [250/469], Reconst Loss(ce): 2573.3853, KL Div: 1490.9917, Total Loss: 4064.3770
Epoch[5/15], Step [300/469], Reconst Loss(ce): 2499.0864, KL Div: 1498.4883, Total Loss: 3997.5747
Epoch[5/15], Step [350/469], Reconst Loss(ce): 2621.9666, KL Div: 1473.2627, Total Loss: 4095.2292
Epoch[5/15], Step [400/469], Reconst Loss(ce): 2609.8223, KL Div: 1537.3784, Total Loss: 4147.2007
Epoch[5/15], Step [450/469], Reconst Loss(ce): 2650.7107, KL Div: 1527.2168, Total Loss: 4177.9277
Epoch[6/15], Step [50/469], Reconst Loss(ce): 2561.3301, KL Div: 1506.4785, Total Loss: 4067.8086
Epoch[6/15], Step [100/469], Reconst Loss(ce): 2432.3572, KL Div: 1521.8077, Total Loss: 3954.1650
Epoch[6/15], Step [150/469], Reconst Loss(ce): 2469.4194, KL Div: 1479.3911, Total Loss: 3948.8105
Epoch[6/15], Step [200/469], Reconst Loss(ce): 2558.3052, KL Div: 1534.6556, Total Loss: 4092.9609
Epoch[6/15], Step [250/469], Reconst Loss(ce): 2539.1494, KL Div: 1479.2701, Total Loss: 4018.4194
Epoch[6/15], Step [300/469], Reconst Loss(ce): 2378.5898, KL Div: 1538.8101, Total Loss: 3917.3999
Epoch[6/15], Step [350/469], Reconst Loss(ce): 2489.4580, KL Div: 1546.4547, Total Loss: 4035.9126
Epoch[6/15], Step [400/469], Reconst Loss(ce): 2492.7891, KL Div: 1450.9631, Total Loss: 3943.7522
Epoch[6/15], Step [450/469], Reconst Loss(ce): 2519.5515, KL Div: 1554.7854, Total Loss: 4074.3369
Epoch[7/15], Step [50/469], Reconst Loss(ce): 2399.9685, KL Div: 1554.4952, Total Loss: 3954.4639
Epoch[7/15], Step [100/469], Reconst Loss(ce): 2336.2871, KL Div: 1524.7257, Total Loss: 3861.0127
Epoch[7/15], Step [150/469], Reconst Loss(ce): 2408.3765, KL Div: 1491.6426, Total Loss: 3900.0190
Epoch[7/15], Step [200/469], Reconst Loss(ce): 2505.7222, KL Div: 1501.8843, Total Loss: 4007.6064
Epoch[7/15], Step [250/469], Reconst Loss(ce): 2307.2178, KL Div: 1490.1670, Total Loss: 3797.3848
Epoch[7/15], Step [300/469], Reconst Loss(ce): 2551.5649, KL Div: 1549.0955, Total Loss: 4100.6602
Epoch[7/15], Step [350/469], Reconst Loss(ce): 2655.7898, KL Div: 1529.9951, Total Loss: 4185.7852
Epoch[7/15], Step [400/469], Reconst Loss(ce): 2496.3823, KL Div: 1550.3567, Total Loss: 4046.7390
Epoch[7/15], Step [450/469], Reconst Loss(ce): 2523.8589, KL Div: 1535.7026, Total Loss: 4059.5615
Epoch[8/15], Step [50/469], Reconst Loss(ce): 2437.6208, KL Div: 1550.0691, Total Loss: 3987.6899

Epoch[8/15], Step [100/469], Reconst Loss(ce): 2460.0352, KL Div: 1476.3782, Total L
oss: 3936.4133
Epoch[8/15], Step [150/469], Reconst Loss(ce): 2331.6504, KL Div: 1485.2751, Total L
oss: 3816.9255
Epoch[8/15], Step [200/469], Reconst Loss(ce): 2325.4351, KL Div: 1505.3879, Total L
oss: 3830.8230
Epoch[8/15], Step [250/469], Reconst Loss(ce): 2446.9729, KL Div: 1524.3706, Total L
oss: 3971.3435
Epoch[8/15], Step [300/469], Reconst Loss(ce): 2386.7678, KL Div: 1555.9454, Total L
oss: 3942.7134
Epoch[8/15], Step [350/469], Reconst Loss(ce): 2229.1470, KL Div: 1517.1946, Total L
oss: 3746.3416
Epoch[8/15], Step [400/469], Reconst Loss(ce): 2343.9485, KL Div: 1535.1390, Total L
oss: 3879.0874
Epoch[8/15], Step [450/469], Reconst Loss(ce): 2390.4011, KL Div: 1513.7819, Total L
oss: 3904.1831
Epoch[9/15], Step [50/469], Reconst Loss(ce): 2348.6199, KL Div: 1579.4883, Total Lo
ss: 3928.1082
Epoch[9/15], Step [100/469], Reconst Loss(ce): 2623.1924, KL Div: 1605.8093, Total L
oss: 4229.0020
Epoch[9/15], Step [150/469], Reconst Loss(ce): 2473.9814, KL Div: 1621.4182, Total L
oss: 4095.3997
Epoch[9/15], Step [200/469], Reconst Loss(ce): 2257.6636, KL Div: 1561.0786, Total L
oss: 3818.7422
Epoch[9/15], Step [250/469], Reconst Loss(ce): 2341.2031, KL Div: 1501.7793, Total L
oss: 3842.9824
Epoch[9/15], Step [300/469], Reconst Loss(ce): 2481.0312, KL Div: 1539.9286, Total L
oss: 4020.9600
Epoch[9/15], Step [350/469], Reconst Loss(ce): 2295.0000, KL Div: 1597.5201, Total L
oss: 3892.5200
Epoch[9/15], Step [400/469], Reconst Loss(ce): 2276.1174, KL Div: 1592.3469, Total L
oss: 3868.4644
Epoch[9/15], Step [450/469], Reconst Loss(ce): 2357.1631, KL Div: 1552.5824, Total L
oss: 3909.7456
Epoch[10/15], Step [50/469], Reconst Loss(ce): 2451.2534, KL Div: 1611.7186, Total L
oss: 4062.9722
Epoch[10/15], Step [100/469], Reconst Loss(ce): 2415.2466, KL Div: 1556.0439, Total
Loss: 3971.2905
Epoch[10/15], Step [150/469], Reconst Loss(ce): 2213.7051, KL Div: 1569.0693, Total
Loss: 3782.7744
Epoch[10/15], Step [200/469], Reconst Loss(ce): 2487.1313, KL Div: 1549.4904, Total
Loss: 4036.6216
Epoch[10/15], Step [250/469], Reconst Loss(ce): 2489.2793, KL Div: 1552.6990, Total
Loss: 4041.9783
Epoch[10/15], Step [300/469], Reconst Loss(ce): 2367.3359, KL Div: 1583.5443, Total
Loss: 3950.8804
Epoch[10/15], Step [350/469], Reconst Loss(ce): 2327.9875, KL Div: 1513.4714, Total
Loss: 3841.4590
Epoch[10/15], Step [400/469], Reconst Loss(ce): 2330.0608, KL Div: 1600.4021, Total
Loss: 3930.4629
Epoch[10/15], Step [450/469], Reconst Loss(ce): 2235.0303, KL Div: 1538.3756, Total
Loss: 3773.4058
Epoch[11/15], Step [50/469], Reconst Loss(ce): 2339.5427, KL Div: 1568.8882, Total L
oss: 3908.4309
Epoch[11/15], Step [100/469], Reconst Loss(ce): 2274.5225, KL Div: 1548.4006, Total
Loss: 3822.9231
Epoch[11/15], Step [150/469], Reconst Loss(ce): 2424.1880, KL Div: 1562.5695, Total
Loss: 3986.7573
Epoch[11/15], Step [200/469], Reconst Loss(ce): 2414.1458, KL Div: 1614.9252, Total
Loss: 4029.0708
Epoch[11/15], Step [250/469], Reconst Loss(ce): 2293.2402, KL Div: 1558.1198, Total
Loss: 3851.3599
Epoch[11/15], Step [300/469], Reconst Loss(ce): 2350.5669, KL Div: 1582.0994, Total
Loss: 3932.6663

Epoch[11/15], Step [350/469], Reconst Loss(ce): 2278.1228, KL Div: 1614.2391, Total Loss: 3892.3618
Epoch[11/15], Step [400/469], Reconst Loss(ce): 2256.2197, KL Div: 1558.0054, Total Loss: 3814.2251
Epoch[11/15], Step [450/469], Reconst Loss(ce): 2334.2126, KL Div: 1583.9532, Total Loss: 3918.1660
Epoch[12/15], Step [50/469], Reconst Loss(ce): 2263.0615, KL Div: 1583.3231, Total Loss: 3846.3848
Epoch[12/15], Step [100/469], Reconst Loss(ce): 2317.2751, KL Div: 1628.5358, Total Loss: 3945.8110
Epoch[12/15], Step [150/469], Reconst Loss(ce): 2301.8354, KL Div: 1541.7571, Total Loss: 3843.5925
Epoch[12/15], Step [200/469], Reconst Loss(ce): 2158.3093, KL Div: 1638.9771, Total Loss: 3797.2864
Epoch[12/15], Step [250/469], Reconst Loss(ce): 2257.4707, KL Div: 1539.7183, Total Loss: 3797.1890
Epoch[12/15], Step [300/469], Reconst Loss(ce): 2345.1011, KL Div: 1526.8855, Total Loss: 3871.9866
Epoch[12/15], Step [350/469], Reconst Loss(ce): 2290.8291, KL Div: 1586.8491, Total Loss: 3877.6782
Epoch[12/15], Step [400/469], Reconst Loss(ce): 2276.2812, KL Div: 1545.3308, Total Loss: 3821.6121
Epoch[12/15], Step [450/469], Reconst Loss(ce): 2265.6890, KL Div: 1570.8804, Total Loss: 3836.5693
Epoch[13/15], Step [50/469], Reconst Loss(ce): 2397.2168, KL Div: 1584.4941, Total Loss: 3981.7109
Epoch[13/15], Step [100/469], Reconst Loss(ce): 2149.8003, KL Div: 1623.5474, Total Loss: 3773.3477
Epoch[13/15], Step [150/469], Reconst Loss(ce): 2286.1924, KL Div: 1531.1681, Total Loss: 3817.3604
Epoch[13/15], Step [200/469], Reconst Loss(ce): 2392.6694, KL Div: 1526.3174, Total Loss: 3918.9868
Epoch[13/15], Step [250/469], Reconst Loss(ce): 2249.8108, KL Div: 1676.2290, Total Loss: 3926.0398
Epoch[13/15], Step [300/469], Reconst Loss(ce): 2374.2156, KL Div: 1569.2686, Total Loss: 3943.4841
Epoch[13/15], Step [350/469], Reconst Loss(ce): 2324.9734, KL Div: 1620.4790, Total Loss: 3945.4524
Epoch[13/15], Step [400/469], Reconst Loss(ce): 2239.3801, KL Div: 1538.7437, Total Loss: 3778.1238
Epoch[13/15], Step [450/469], Reconst Loss(ce): 2138.2505, KL Div: 1506.5101, Total Loss: 3644.7607
Epoch[14/15], Step [50/469], Reconst Loss(ce): 2443.0164, KL Div: 1593.8063, Total Loss: 4036.8228
Epoch[14/15], Step [100/469], Reconst Loss(ce): 2369.7334, KL Div: 1561.4868, Total Loss: 3931.2202
Epoch[14/15], Step [150/469], Reconst Loss(ce): 2233.6301, KL Div: 1549.7058, Total Loss: 3783.3359
Epoch[14/15], Step [200/469], Reconst Loss(ce): 2364.6152, KL Div: 1597.7118, Total Loss: 3962.3271
Epoch[14/15], Step [250/469], Reconst Loss(ce): 2344.9248, KL Div: 1646.5491, Total Loss: 3991.4739
Epoch[14/15], Step [300/469], Reconst Loss(ce): 2386.6240, KL Div: 1620.0592, Total Loss: 4006.6831
Epoch[14/15], Step [350/469], Reconst Loss(ce): 2496.7554, KL Div: 1625.2561, Total Loss: 4122.0117
Epoch[14/15], Step [400/469], Reconst Loss(ce): 2294.2473, KL Div: 1561.0820, Total Loss: 3855.3293
Epoch[14/15], Step [450/469], Reconst Loss(ce): 2296.6646, KL Div: 1553.2640, Total Loss: 3849.9287
Epoch[15/15], Step [50/469], Reconst Loss(ce): 2293.9192, KL Div: 1548.7849, Total Loss: 3842.7041
Epoch[15/15], Step [100/469], Reconst Loss(ce): 2305.1538, KL Div: 1571.8022, Total Loss: 3876.9561

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Epoch[15/15], Step [150/469], Reconst Loss(ce): 2415.1274, KL Div: 1557.4393, Total
Loss: 3972.5669
Epoch[15/15], Step [200/469], Reconst Loss(ce): 2298.8652, KL Div: 1642.4681, Total
Loss: 3941.3335
Epoch[15/15], Step [250/469], Reconst Loss(ce): 2314.0459, KL Div: 1599.9338, Total
Loss: 3913.9797
Epoch[15/15], Step [300/469], Reconst Loss(ce): 2224.2659, KL Div: 1557.6239, Total
Loss: 3781.8896
Epoch[15/15], Step [350/469], Reconst Loss(ce): 2164.1431, KL Div: 1538.4395, Total
Loss: 3702.5825
Epoch[15/15], Step [400/469], Reconst Loss(ce): 2200.5530, KL Div: 1547.6421, Total
Loss: 3748.1951
Epoch[15/15], Step [450/469], Reconst Loss(ce): 2313.5911, KL Div: 1577.8301, Total
Loss: 3891.4211
```

```
F:\anaconda\lib\site-packages\sklearn\manifold\_t_sne.py:780: FutureWarning: The def
ault initialization in TSNE will change from 'random' to 'pca' in 1.2.
  warnings.warn(
F:\anaconda\lib\site-packages\sklearn\manifold\_t_sne.py:790: FutureWarning: The def
ault learning rate in TSNE will change from 200.0 to 'auto' in 1.2.
  warnings.warn(
```
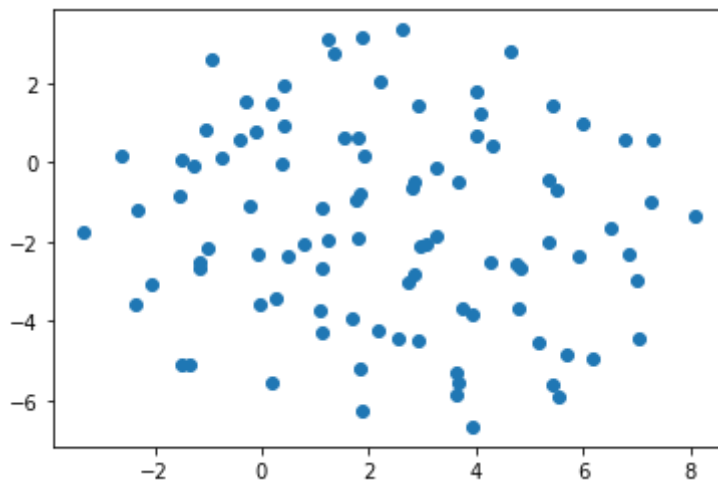

提高要求4：和其他网络对比

VAE (Variational Autoencoder)，GCN (Graph Convolutional Network)，GAN (Generative Adversarial Network) 和 Diffusion Model 是四种不同的深度学习模型，用于不同的应用程序。

VAE 是一种生成模型，用于从观测数据中学习潜在分布，并使用这些学习的特征生成新的样本。它基于自动编码器架构，其中一个编码器将输入数据映射到一个潜在空间，然后一个解码器将其还原为原始数据。

GCN (Graph Convolutional Network) 是一种用于处理图数据的深度学习模型。它使用卷积运算来捕获图中节点和边之间的关系，并使用这些关系进行图分类或图分割。它可以用于许多应用程序，如社交网络分析、药物发现和蛋白质结构预测。

GAN (Generative Adversarial Network) 是一种生成模型，由两个对抗的网络组成：一个生成器和一个判别器。生成器生成新的样本，而判别器试图分辨出哪些样本是真实的，哪些是生成的。通过不断调整这两个网络，GAN 可以学习生成与观测数据相似的样本。

Diffusion Model 是一种用于处理图数据的模型，用于预测节点的属性。它基于信息在图上的扩散过程，通过将属性值在节点之间传播来预测未知的属性。

In [ ]: