



HAL
open science

Diffusion-based speech enhancement with a weighted generative-supervised learning loss

Jean-Eudes Ayilo, Mostafa Sadeghi, Romain Serizel

► To cite this version:

Jean-Eudes Ayilo, Mostafa Sadeghi, Romain Serizel. Diffusion-based speech enhancement with a weighted generative-supervised learning loss. International Conference on Acoustics Speech and Signal Processing (ICASSP), IEEE, Apr 2024, Seoul (Korea), South Korea. hal-04210729v1

HAL Id: hal-04210729

<https://hal.science/hal-04210729v1>

Submitted on 19 Sep 2023 (v1), last revised 19 Jan 2024 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

DIFFUSION-BASED SPEECH ENHANCEMENT WITH A WEIGHTED GENERATIVE-SUPERVISED LEARNING LOSS

Jean-Eudes Ayilo, Mostafa Sadeghi, Romain Serizel

Université de Lorraine, CNRS, Inria, LORIA, F-54000 Nancy, France

ABSTRACT

Diffusion-based generative models have recently gained attention in speech enhancement (SE), providing an alternative to conventional supervised methods. These models transform clean speech training samples into Gaussian noise centered at noisy speech, and subsequently learn a parameterized model to reverse this process, conditionally on noisy speech. Unlike supervised methods, generative-based SE approaches usually rely solely on an unsupervised loss, which may result in less efficient incorporation of conditioned noisy speech. To address this issue, we propose augmenting the original diffusion training objective with a mean squared error (MSE) loss, measuring the discrepancy between estimated enhanced speech and ground-truth clean speech at each reverse process iteration. Experimental results demonstrate the effectiveness of our proposed methodology.

Index Terms— Speech enhancement, diffusion models, generative modeling, supervised learning.

1. INTRODUCTION

Diffusion models are a recent class of generative models that have brought significant improvements in image and audio synthesis [1, 2]. Their underlying mechanism is to gradually turn training samples into noise, and then learn a parameterized model to revert this process, thus enabling data generation from pure noise. These models are also gaining increasing interest in the speech enhancement (SE) task, whose goal is to recover a clean speech signal recorded in adverse acoustic environments. In this context, diffusion models aim at learning the distribution of speech data, encoding their temporal-spectral characteristics, in order to infer clean speech from noisy observation [3]. Additionally, this distribution is learned conditionally on the associated noisy speech data to guide the data generation process [3–6].

This generative-based SE approach is systematically different from the prevailing supervised counterpart [7, 8], which

learns a deep neural network (DNN) to directly estimate clean speech from noisy input by minimizing a supervised loss, e.g., mean squared error (MSE). In contrast, diffusion-based SE usually follows the standard unsupervised (generative-based) loss used in diffusion models, with the difference that noisy speech is provided as an additional input. While this could be potentially advantageous, as the intrinsic properties of clean speech are also modeled, contrary to supervised methods, it may not efficiently leverage the conditioned information of noisy speech. In other words, the training loss in the diffusion process does not properly measure the goodness of the estimated clean speech. As such, without a proper *supervision*, it may lead to the so-called *condition collapse* phenomenon [9], i.e., ignoring some parts of conditioning information.

The current study aims at addressing this issue, and bridging the performance gap between the supervised and diffusion-based approaches by combining the best of the two worlds. To this end, we propose to add an MSE loss to the original generative-based diffusion loss. This extra supervised loss measures the distance between an estimation of the enhanced speech signal at each iteration of the reverse process and the ground-truth clean speech. In doing so, we hope to combine the effectiveness of diffusion models in unseen noise conditions and the strength of supervised methods in seen noise conditions. Experiments are performed to evaluate the effectiveness of the proposed approach against both supervised and standard diffusion-based approaches. The results show promising performance of the proposed training methodology.

In the rest of the paper, we present an overview of diffusion-based SE methods in Section 2, followed by a more detailed review of [10]. Our proposed methodology is discussed in Section 3. Next, Section 4 presents the experiments and results, and Section 5 concludes the paper.

2. RELATED WORK

2.1. Diffusion-based speech enhancement

The fundamental concept behind diffusion models involves two main phases. Initially, within a forward process, clean data is progressively distorted by adding (usually) Gaussian noise, eventually resulting in entirely noise data following a tractable distribution like a standard Gaussian. Subsequently,

This research was supported by the French National Research Agency (ANR) under the project REAVISE (ANR-22-CE23-0026-01). Experiments presented in this paper were carried out using the Grid’5000 testbed, supported by a scientific interest group hosted by Inria, and including CNRS, RENATER, and several universities as well as other organizations (see <https://www.grid5000.fr>).

through a reverse process, a DNN is trained to sequentially produce clean data, beginning from random noise sampled from the prior distribution.

Many recent studies have already used the diffusion principle for speech enhancement. [3] used Gaussian Markov chains to model the forward and reverse processes, where the mean of the forward Gaussian Markov chain is a linear interpolation between the clean speech and the associated noisy one. The training objective is obtained by minimizing the Kullback–Leibler (KL) divergence between the forward and reverse Markov chains, which leads to an objective where the trained network learns to predict both Gaussian noise and non-Gaussian noise. [5] added an auxiliary classification loss to the loss function of [3] to perform noise classification and help the model better use the noise information, which resulted in improved performance. [4] leveraged stochastic differential equation (SDE) [1] to model the forward and reverse processes, and used denoising score matching [11] as the training objective.

All these works condition the diffusion process on the noisy speech to take into account the non-Gaussian nature of environmental noise. More precisely, to estimate clean speech, the reverse process is performed starting from a Gaussian noise centred on the noisy speech, which allows for iteratively recovering an enhanced version. [6] proposed to extend the forward process by incorporating a deterministic, progressive degradation of the clean speech through linear interpolation between the clean speech and the noisy speech. The training objective here consists in minimizing an ℓ_1 loss between the clean speech and the reconstruction of the clean speech at a given step of the forward degradation. The recent work [9] identified the condition collapse problem, and proposed an auxiliary conditional generation network for generating reliable condition representations as well as a dual-path parallel network architecture to provide fine-grained condition guidance for the diffusion model. Additionally, a refinement network is trained in a supervised way that takes the enhanced speech returned by the reverse sampling and outputs a refined version. We adopt a different strategy than these approaches by including an ℓ_2 supervision loss in the generative denoising score matching objective.

2.2. Score-based generative model for SE (SGMSE)

In this section, we review the score-based diffusion model proposed in [4], as a closely related approach to our work. Let us consider a triple of flattened short-time Fourier transform (STFT) representations of clean speech, noisy speech, and noise: $\mathbf{x}_0, \mathbf{y}, \mathbf{n} \in \mathbb{C}^d$, where d denotes the total number of complex-valued time-frequency (TF) bins. We assume that the noisy speech STFT is formed by the following mixture model: $\mathbf{y} = \mathbf{x}_0 + \mathbf{n}$. The objective of SE is then to recover \mathbf{x}_0 given \mathbf{y} .

As previously mentioned, the forward process of diffusion

involves gradually introducing Gaussian noise to the clean speech. This process is modeled by a stochastic differential equation (SDE), and its solution is represented as the stochastic process $\{\mathbf{x}_t\}_t$ [4]:

$$d\mathbf{x}_t = \underbrace{\gamma(\mathbf{y} - \mathbf{x}_t)}_{:=\mathbf{f}(\mathbf{x}_t, \mathbf{y})} dt + \underbrace{\left[\sigma_{\min} \left(\frac{\sigma_{\max}}{\sigma_{\min}} \right)^t \sqrt{2 \log \left(\frac{\sigma_{\max}}{\sigma_{\min}} \right)} \right]}_{:=g(t)} d\mathbf{w} \quad (1)$$

where \mathbf{x}_t denotes the process state at time $t \in (0, T]$, $\gamma \in \mathbb{R}$ controls the transition from \mathbf{x}_0 to \mathbf{y} , and $g(t) \in \mathbb{R}$, with constant parameters σ_{\min} and σ_{\max} , is the diffusion coefficient that controls the amount of noise induced by a standard Wiener process \mathbf{w} . Moreover, $\mathbf{f}(\mathbf{x}_t, \mathbf{y})$ is the drift term, which makes the forward process conditioned on the noisy speech. For numerical stability, the forward process starts at $t_\varepsilon \neq 0$.

The final SE objective is to reverse the above forward process in order to estimate the clean speech. To this end, one needs to find the solution to the following associated reverse process SDE [12]:

$$d\mathbf{x}_t = [-\mathbf{f}(\mathbf{x}_t, \mathbf{y}) + g(t)^2 \nabla_{\mathbf{x}_t} \log p_t(\mathbf{x}_t | \mathbf{y})] dt + g(t) d\bar{\mathbf{w}} \quad (2)$$

where $\bar{\mathbf{w}}$ denotes a standard Wiener process running backwards in time. In (2), the term $\nabla_{\mathbf{x}_t} \log p_t(\mathbf{x}_t | \mathbf{y})$ refers to the conditional score function, which is approximated by a so-called (conditional) score model $\mathbf{s}_\theta(\mathbf{x}_t, \mathbf{y}, t)$ with parameters denoted θ . The score model can be trained by minimizing a Fisher divergence between the true and approximate score, utilising the denoising score matching principle [11]. Doing so, the training objective reduces to:

$$\min_{\theta} \mathbb{E}_{t, (\mathbf{x}_0, \mathbf{y}), \mathbf{z}, \mathbf{x}_t | (\mathbf{x}_0, \mathbf{y})} \left[L_\theta(\mathbf{x}_t, \mathbf{y}, t, \mathbf{z}) \right], \quad (3)$$

where

$$L_\theta(\mathbf{x}_t, \mathbf{y}, t, \mathbf{z}) := \left\| \mathbf{s}_\theta(\mathbf{x}_t, \mathbf{y}, t) + \frac{\mathbf{z}}{\sigma(t)} \right\|^2 \quad (4)$$

and $\mathbf{z} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{z}; \mathbf{0}, \mathbf{I})$, with $\mathcal{N}_{\mathbb{C}}$ denoting the circularly-symmetric complex normal distribution. As the drift term is linear, the transition kernel $p_{0t}(\mathbf{x}_t | \mathbf{x}_0, \mathbf{y})$ admits a closed-form expression [1]:

$$p_{0t}(\mathbf{x}_t | \mathbf{x}_0, \mathbf{y}) = \mathcal{N}_{\mathbb{C}}\left(\mathbf{x}_t; \boldsymbol{\mu}(\mathbf{x}_0, \mathbf{y}, t), \sigma(t)^2 \mathbf{I}\right), \quad (5)$$

where

$$\boldsymbol{\mu}(\mathbf{x}_0, \mathbf{y}, t) = e^{-\gamma t} \mathbf{x}_0 + (1 - e^{-\gamma t}) \mathbf{y} \quad (6)$$

and

$$\sigma(t)^2 = \frac{\sigma_{\min}^2 \left((\sigma_{\max}/\sigma_{\min})^{2t} - e^{-2\gamma t} \right) \log(\sigma_{\max}/\sigma_{\min})}{\gamma + \log(\sigma_{\max}/\sigma_{\min})}. \quad (7)$$

Once the score model is trained, it is plugged in (2), replacing the score function, and the resulting reverse SDE is solved by a Predictor-Corrector sampling procedure [1] to iteratively generate clean speech’s estimates.

3. WEIGHTED GENERATIVE-SUPERVISED LEARNING LOSS

The training objective function described in (3) and (4) aims to train the score model by minimizing the discrepancy between the approximated score and the score derived from the transition kernel, represented as $\nabla_{\mathbf{x}_t} \log p_{0t}(\mathbf{x}_t|\mathbf{x}_0, \mathbf{y}) = -\mathbf{z}/\sigma(t)$. This suggests that, in its current form, the score model is not explicitly informed of the specific SE task it is meant to perform. Instead, the training loss primarily resembles the generative (unsupervised) loss typically utilized in unconditional diffusion models.

To address this issue, we propose the inclusion of a supervised loss as a form of regularization or guidance. This additional loss explicitly reinforces the SE objective during the score model’s training. To accomplish this objective, we need to have an estimate of the clean speech at each iteration of the reverse process, denoted $\hat{\mathbf{x}}_{0,t}$, to be compared against the ground-truth \mathbf{x}_0 . Such an estimate could be provided using Tweedie’s approach [13]. To this end, by combining (5) and (6), we can write

$$\mathbf{x}_t = e^{-\gamma t} \mathbf{x}_0 + (1 - e^{-\gamma t}) \mathbf{y} + \mathbf{e}_t \quad (8)$$

where $\mathbf{e}_t \sim \mathcal{N}_{\mathbb{C}}(\mathbf{e}_t; \mathbf{0}, \sigma(t)^2 \mathbf{I})$. If we apply Tweedie’s formula independently to the real and imaginary parts of the variables, we obtain the following result:

$$\begin{aligned} e^{-\gamma t} \hat{\mathbf{x}}_{0,t} + (1 - e^{-\gamma t}) \mathbf{y} &= \mathbf{x}_t + (\sigma(t)^2/2) \nabla_{\mathbf{x}_t} \log p_t(\mathbf{x}_t|\mathbf{y}) \\ &\approx \mathbf{x}_t + (\sigma(t)^2/2) \mathbf{s}_{\theta}(\mathbf{x}_t, \mathbf{y}, t). \end{aligned} \quad (9)$$

We then propose to add an MSE loss between the above expression and the associated ground-truth one, i.e., $e^{-\gamma t} \mathbf{x}_0 + (1 - e^{-\gamma t}) \mathbf{y}$, to the original score loss (3). This leads to the following weighted training objective for learning the conditional score model

$$\begin{aligned} \min_{\theta} \mathbb{E}_{t, (\mathbf{x}_0, \mathbf{y}), \mathbf{z}, \mathbf{x}_t | (\mathbf{x}_0, \mathbf{y})} [& (1 - \alpha_t) L_{\theta}(\mathbf{x}_t, \mathbf{y}, t, \mathbf{z}) + \\ & \left\| \mathbf{x}_t + \frac{\sigma(t)^2}{2} \mathbf{s}_{\theta}(\mathbf{x}_t, \mathbf{y}, t) - (e^{-\gamma t} \mathbf{x}_0 + (1 - e^{-\gamma t}) \mathbf{y}) \right\|^2] \end{aligned} \quad (10)$$

which is a weighted loss between the original generative-based training loss in (4) and a supervised ℓ_2 loss. α_t are time-dependent scalar weights taking values in $[0, 1]$. We propose to use the following expression for the weights

$$\alpha_t = \frac{\sigma(T) - \sigma(t)}{\sigma(T) - \sigma(t_{\varepsilon})}. \quad (11)$$

In the proposed loss function (10), we aim to make a balance between two essential tasks: conditional score estimation and supervised estimation of clean speech at every reverse iteration. The parameter α_t , as a function of time, increases as the Gaussian noise variance $\sigma(t)$ decreases during the reverse process. Consequently, at earlier stages of the reverse diffusion process, the network is expected to give higher weights to the loss associated with score estimation, while in the later stages, the score network is tasked with assigning more importance to the supervised component of the loss.

4. EXPERIMENTS

Baselines. We evaluate the performance of our proposed weighted generative-supervised learning loss for SE, comparing it to a reference approach referred to as SGMSE+ [4]. Both methods utilize the same network architecture, based on the Noise Conditional Score Network (NCSN++), which consists of a multi-resolution U-Net design. Additionally, we compare these two methods with a purely supervised model that directly predicts the clean speech spectrogram from the noisy speech spectrogram input. For the supervised approach, we also use the NCSN++ network, which is trained by minimizing the MSE loss between the enhanced and clean spectrograms.

Evaluation metrics. To measure the quality of the enhanced speech signals, we use standard instrumental evaluation metrics, including the scale-invariant signal-to-distortion ratio (SI-SDR) in dB [14], the extended short-time objective intelligibility (ESTOI) measure [15] ($[0, 1]$), and the perceptual evaluation of speech quality (PESQ) score [16] ($[-0.5, 4.5]$). In addition, we use the DNS-MOS, as a non-intrusive objective evaluation metric [17], which provides three MOS scores: speech signal quality (SIG), background intrusiveness (BAK), and overall quality (OVRL). For all these metrics, the higher, the better.

Datasets. For training and evaluation, we used the WSJ0-QUT [18] and NTCD-TIMIT datasets [19], to allow for a cross-dataset evaluation. The WSJ0-QUT dataset combines the clean speech signals from the WSJ0 dataset [20] with noise signals from the QUT-NOISE dataset [21]. The test subset of WSJ0-QUT comprise 651 synthetic mixtures (roughly 1.5 hours). It is created by taking clean speech signals from the ‘si_et_05’ subset of WSJ0 (unseen speech samples) and adding noise signals sampled uniformly from the ‘verification’ set of the QUT-NOISE dataset with signal-to-noise ratio (SNR) values of -5, 0, and 5 dB.

The NTCD-TIMIT dataset comprises 62 English speakers (with/without Irish accent), divided into train, test, and validation subsets, where each speaker utters 98 different sentences. Duration of each utterance is approximately 5 seconds. To create the training and validation datasets, we combined the clean speech signals from the NTCD-TIMIT dataset

Table 1: Speech enhancement results (mean \pm standard error) for WSJ0-QUT and NTCD-TIMIT under both matched and mismatched conditions. The best average metric value is highlighted in bold, and the second best is italicized.

Training set	Metric	SI-SDR (dB)	PESQ	ESTOI	SIG-MOS	BAK-MOS	OVR-MOS
WSJ0-QUT	Input (WSJ0-QUT)	-2.60 \pm 0.16	1.83 \pm 0.02	0.50 \pm 0.01	4.04 \pm 0.01	2.93 \pm 0.02	3.13 \pm 0.01
	Supervised	12.91 \pm 0.14	2.67 \pm 0.02	0.84 \pm 0.00	4.38 \pm 0.01	4.81 \pm 0.01	4.30 \pm 0.01
	SGMSE+ [10]	10.21 \pm 0.16	2.83 \pm 0.02	0.81 \pm 0.00	<i>4.52 \pm 0.01</i>	4.70 \pm 0.01	<i>4.31 \pm 0.01</i>
	Proposed	<i>10.40 \pm 0.15</i>	2.88 \pm 0.02	<i>0.83 \pm 0.00</i>	4.56 \pm 0.01	<i>4.73 \pm 0.00</i>	4.37 \pm 0.01
NTCD-TIMIT	Supervised	9.27 \pm 0.15	2.36 \pm 0.02	0.75 \pm 0.00	4.22 \pm 0.01	4.68 \pm 0.01	4.15 \pm 0.02
	SGMSE+ [10]	7.32 \pm 0.15	2.51 \pm 0.02	0.72 \pm 0.01	<i>4.47 \pm 0.01</i>	4.60 \pm 0.01	<i>4.24 \pm 0.01</i>
	Proposed	<i>7.55 \pm 0.14</i>	2.61 \pm 0.02	0.75 \pm 0.00	4.55 \pm 0.01	<i>4.66 \pm 0.00</i>	4.34 \pm 0.01
	Input (NTCD-TIMIT)	-7.81 \pm 0.22	1.77 \pm 0.02	0.31 \pm 0.00	3.51 \pm 0.01	2.28 \pm 0.02	2.69 \pm 0.01
NTCD-TIMIT	Supervised	8.57 \pm 0.19	2.18 \pm 0.02	<i>0.54 \pm 0.01</i>	3.69 \pm 0.01	4.26 \pm 0.01	3.42 \pm 0.02
	SGMSE+ [10]	6.21 \pm 0.23	2.35 \pm 0.02	0.53 \pm 0.01	<i>4.02 \pm 0.01</i>	<i>4.30 \pm 0.01</i>	<i>3.68 \pm 0.01</i>
	Proposed	<i>7.97 \pm 0.18</i>	2.46 \pm 0.02	0.57 \pm 0.01	4.14 \pm 0.01	4.37 \pm 0.01	3.83 \pm 0.01
	Input (WSJ0-QUT)	5.98 \pm 0.22	2.02 \pm 0.02	0.50 \pm 0.01	3.76 \pm 0.01	<i>4.19 \pm 0.01</i>	3.34 \pm 0.02
WSJ0-QUT	Supervised	5.98 \pm 0.22	2.02 \pm 0.02	0.50 \pm 0.01	3.76 \pm 0.01	<i>4.19 \pm 0.01</i>	3.34 \pm 0.02
	SGMSE+ [10]	1.28 \pm 0.27	2.05 \pm 0.02	0.45 \pm 0.01	<i>4.04 \pm 0.01</i>	4.05 \pm 0.01	3.57 \pm 0.02
	Proposed	<i>4.42 \pm 0.23</i>	2.08 \pm 0.02	<i>0.48 \pm 0.01</i>	4.16 \pm 0.01	4.20 \pm 0.01	3.76 \pm 0.01

with various types of noise from the DEMAND dataset [22]. We applied different SNR values, including -10, -5, 0, 5, and 10 dB. Each utterance in the training and validation sets was mixed with three different combinations of DEMAND noises and SNRs, resulting in a total of 12,348 training and 2,352 validation mixtures. For the test subset, we retained the same noisy speech signals as provided in the NTCD-TIMIT dataset. These noisy samples were generated by adding six different noise types, including Living Room, White, Cafe, Car, Babble, and Street, with SNRs of -5 dB, 0 dB, and 5 dB. The test set comprises 810 mixtures.

Hyperparameters setting for SDE and STFT. Input data representations, SDE and STFT representations follow the same settings as in [10]. Specifically, the STFT of the speech data, with a sampling rate of 16kHz, is computed with a window size of 512, a hop length of 128 (75% overlap) and a Hann window which gives $F = 256$ as the number of frequency bins. For the drift and diffusion coefficients of SDE in (1), the parameters are set as $\gamma = 1.5$, $\sigma_{\min} = 0.05$, $\sigma_{\max} = 0.5$. The minimum and maximum process times are set to $t_{\varepsilon} = 0.03$ and $T = 1$, respectively.

Results. In Table 1, we present the average speech enhancement metrics for all the cross-dataset configuration settings, along with the corresponding standard error of the mean. To clarify, we use the term “matched condition” when the model is trained and tested on the same dataset, while “mismatched condition” refers to cases where the model is evaluated on a test set from a different dataset than the one it was trained on.

From Table 1, we can draw several conclusions. First, in both matched and mismatched conditions, the supervised method consistently outperforms the two diffusion-based methods when considering the SI-SDR, ESTOI, and BAK-MOS metrics. Our proposed method ranks second in performance. Nevertheless, when trained and evaluated on the NTCD-TIMIT dataset, the ESTOI and BAK-MOS metrics

show a different trend. In these cases, the supervised method underperforms our proposed method. For the PESQ, SIG-MOS, and OVR-MOS metrics, the proposed method consistently performs the best.

A noteworthy observation from these findings is that in the matched conditions, when the supervised method performs the best, the gap between the supervised and SGMSE+ tends to narrow when the supervision loss is added. This trend also holds for the mismatched conditions.

In summary, our proposed method appears to inherit some capabilities from the supervised method, striving to match its performance in terms of SI-SDR, ESTOI, and BAK-MOS. Simultaneously, it retains and even improves upon the strengths of the baseline SGMSE+ method, resulting in better performance in terms of ESTOI, PESQ, SIG-MOS, and OVR-MOS. This suggests that the supervision loss provides valuable feedback for score estimation.

5. CONCLUSION

In this paper, we addressed the problem of diffusion-based speech enhancement. We introduced a supervised training loss component alongside the original generative-based score estimation loss to better leverage the noisy speech data. This weighted loss balances the score estimation loss with an MSE-based supervision loss, enhancing the mapping between clean and noisy speech by incorporating clean speech estimates during the reverse process. This additional loss aids in training a score model better optimized for speech enhancement. Our experiments, conducted in both matched and mismatched conditions, demonstrate that our approach combines the strengths of supervised methods and diffusion-based approaches, resulting in improved performance. Future research directions involve exploring alternative supervised loss functions to MSE and developing more efficient adaptive weighting mechanisms.

6. REFERENCES

- [1] Y. Song, J. Sohl-Dickstein, D. P. Kingma, A. Kumar, S. Ermon, and B. Poole, “Score-based generative modeling through stochastic differential equations,” in *International Conference on Learning Representations (ICLR)*, 2021.
- [2] Z. Kong, W. Ping, J. Huang, K. Zhao, and B. Catanzaro, “Diffwave: A versatile diffusion model for audio synthesis,” in *International Conference on Learning Representations*, 2020.
- [3] Y.-J. Lu, Z.-Q. Wang, S. Watanabe, A. Richard, C. Yu, and Y. Tsao, “Conditional diffusion probabilistic model for speech enhancement,” in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2022, pp. 7402–7406.
- [4] J. Richter, S. Welker, J.-M. Lemercier, B. Lay, and T. Gerkmann, “Speech enhancement and dereverberation with diffusion-based generative models,” *arXiv preprint arXiv:2208.05830*, 2022.
- [5] Y. Hu, C. Chen, R. Li, Q. Zhu, and E. S. Chng, “Noise-aware speech enhancement using diffusion probabilistic model,” *arXiv preprint arXiv:2307.08029*, 2023.
- [6] H. Yen, F. G. Germain, G. Wichern, and J. Le Roux, “Cold diffusion for speech enhancement,” in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2023, pp. 1–5.
- [7] Y. Xu, J. Du, L.-R. Dai, and C.-H. Lee, “A regression approach to speech enhancement based on deep neural networks,” *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, vol. 23, no. 1, pp. 7–19, 2014.
- [8] D. Wang and J. Chen, “Supervised speech separation based on deep learning: An overview,” *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, vol. 26, no. 10, pp. 1702–1726, 2018.
- [9] W. Tai, F. Zhou, G. Trajcevski, and T. Zhong, “Revisiting denoising diffusion probabilistic models for speech enhancement: Condition collapse, efficiency and refinement,” in *Proceedings of the AAAI Conference on Artificial Intelligence*, 2023, vol. 37, pp. 13627–13635.
- [10] J. Richter, S. Welker, J.-M. Lemercier, B. Lay, and T. Gerkmann, “Speech enhancement and dereverberation with diffusion-based generative models,” *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, 2023.
- [11] P. Vincent, “A connection between score matching and denoising autoencoders,” *Neural computation*, vol. 23, no. 7, pp. 1661–1674, 2011.
- [12] B. D. Anderson, “Reverse-time diffusion equation models,” *Stochastic Processes and their Applications*, vol. 12, no. 3, pp. 313–326, 1982.
- [13] B. Efron, “Tweedie’s formula and selection bias,” *Journal of the American Statistical Association*, vol. 106, no. 496, pp. 1602–1614, 2011.
- [14] J. Le Roux, S. Wisdom, H. Erdogan, and J. R. Hershey, “SDR–half-baked or well done?,” in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2019, pp. 626–630.
- [15] J. Jensen and C. H. Taal, “An algorithm for predicting the intelligibility of speech masked by modulated noise maskers,” *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, vol. 24, no. 11, pp. 2009–2022, 2016.
- [16] A. W. Rix, J. G. Beerends, M. P. Hollier, and A. P. Hekstra, “Perceptual evaluation of speech quality (PESQ)—a new method for speech quality assessment of telephone networks and codecs,” in *IEEE international conference on acoustics, speech, and signal processing. Proceedings (ICASSP)*, 2001, vol. 2, pp. 749–752.
- [17] C. K. Reddy, V. Gopal, and R. Cutler, “DNSMOS P. 835: A non-intrusive perceptual objective speech quality metric to evaluate noise suppressors,” in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2022, pp. 886–890.
- [18] S. Leglaive, X. Alameda-Pineda, L. Girin, and R. Horaud, “A recurrent variational autoencoder for speech enhancement,” in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2020.
- [19] A. H. Abdelaziz et al., “NTCD-TIMIT: A new database and baseline for noise-robust audio-visual speech recognition.,” in *Interspeech*, 2017, pp. 3752–3756.
- [20] Garofolo, John S., Graff, David, Paul, Doug, and Pallett, David, “CSR-I (WSJ0) Complete,” May 2007, Artwork Size: 9542041 KB Pages: 9542041 KB.
- [21] D. Dean, A. Kanagasundaram, H. Ghaemmaghami, M. H. Rahman, and S. Sridharan, “The QUT-NOISE-SRE protocol for the evaluation of noisy speaker recognition,” in *Proceedings of Interspeech*, 2015, pp. 3456–3460.
- [22] J. Thiemann, N. Ito, and E. Vincent, “The diverse environments multi-channel acoustic noise database (DEMAND): A database of multichannel environmental noise recordings,” in *Proceedings of Meetings on Acoustics*. AIP Publishing, 2013, vol. 19.