

Fourier VAE Models for Turbofan RUL

One-Page Summary

Key Questions Addressed

Theme	Question
Latent Geometry for RUL	Can combining smooth and spike latent spaces improve RUL prediction for degradation time series?
Interpretability of Spike Latents	Do spike latents meaningfully align with degradation phases, providing predictive power and interpretability?
Cross-Domain Applicability	Can this framework generalize to finance and healthcare time series with similar smooth-shock dynamics?

Conceptual Ideas Proposed

- The **FourierSpike-VAE** models degradation using two latent spaces: a Fourier latent for smooth trends and a spike latent for abrupt anomalies, enabling geometry-aware separation of gradual wear and sudden shocks.
- The model applies **opposing KL schedules**, increasing regularization for Fourier latents while decreasing it for spike latents, encouraging structured latent separation during training.
- Training uses **30-cycle sliding windows**, allowing local degradation modeling without engine-specific dependencies.
- Specific spike latent dimensions (e.g., $z_{spike}[0]$) align with mid-life degradation phases, activating as early-warning signals and fading outside that window.

Key Results

- **Latent space visualizations** show clear separation, with spike activations clustering near end-of-life and Fourier latents spanning broader trends.
- Linear regression on spike latents yields $MAE = 34.35$ and $R^2 = 0.564$; XGBoost improves this to $MAE = 31.85$ and $R^2 = 0.587$, confirming **spike latents carry predictive structure**.
- Conditioning on both spike and Fourier latents provides no significant gain, confirming spike latents are sufficient for RUL estimation.
- The architecture **extends to finance and healthcare** tasks where smooth trends and shocks must be modeled together as explored in follow-up work on arrhythmias and commodity prices.

Illustrative Figures

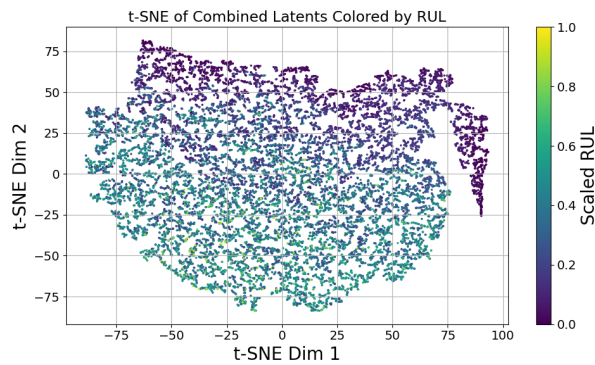


Figure 1: **t-SNE projection of combined latent embeddings** $[z_{spike}, z_{fourier}]$, colored by scaled RUL. The latent space forms a smooth manifold aligned with degradation stages, with low-RUL regions clustering distinctly.

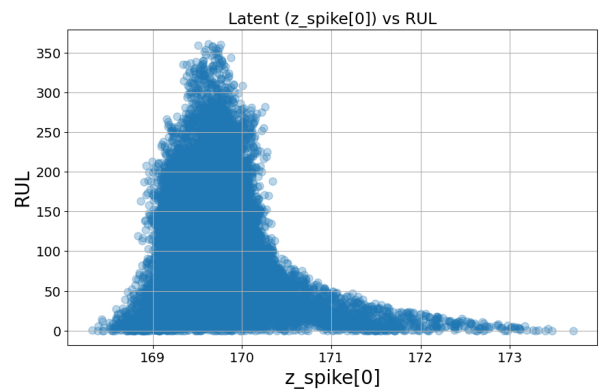


Figure 2: **Relationship between spike latent dimension** $z_{spike}[0]$ **and RUL**. A bell-shaped pattern emerges, suggesting $z_{spike}[0]$ activates as degradation becomes detectable and fades near end-of-life.