# FAULT DIAGNOSIS OF AIRCRAFT ENGINE FAN BLADES USING ANSYS-BASED MODAL ANALYSIS AND RANDOM FOREST ALGORITHM

Bùi Nhật Minh (2410581) · Nguyễn Hoàng Minh (2410601) | Supervisor: Dr. Bùi Quang Thành
Department of Technology and Engineering · Aeronautical Engineering

## 1 INTRODUCTION

Repeated aerodynamic and vibrational loads can initiate and grow fatigue cracks in aircraft engine fan blades. Fatigue is reported to cause about half of the damage to jet-engine components, and blade separation has been associated with 315 uncontained engine-failure events.

**This study represents cracks on the blade's curved surface and quantifies the noise limit for detection. At σ_rel = 0.001 (0.1%), prediction averaging improves balanced accuracy from 60.4% to 87.6%.**

## 2 RESEARCH OBJECTIVES

### Q1 Represent

How can crack position, length and depth be represented accurately on a curved, twisted blade?

### Q2 Quantify

How much do the modal frequencies change, and how do the changes depend on crack location and size?

### Q3 Detectability

Which cracks can still be distinguished when realistic measurement noise is added?

## 3 METHODOLOGY & EVIDENCE

The study combines a verified finite-element model with a case-grouped machine-learning pipeline to test crack detection, size estimation and the limits of the available evidence.

1. **Blade model**
   CATIA geometry · 2.88 m span · Ti-6Al-4V · clamped at the root
2. **Finite-element analysis**
   654,966 SOLID187 elements · Block Lanczos solver · first 10 modes
3. **Curved-surface crack**
   Ecrack = $10^{-3}$E · mass unchanged · depth measured along the local surface normal
4. **Parametric crack design**
   600 Latin Hypercube samples across span, chord, crack length and depth
5. **Dataset generation**
   615 cases · 90 readings per case · σ_rel = 0.001/0.005/0.010 (0.1%/0.5%/1.0%)
6. **Leakage-safe evaluation**
   492/123 case-grouped split · five-fold grouped CV · threshold calibrated from out-of-fold predictions

### Dataset quality and validation

- 615 physical cases yield 55,350 correlated readings; the blade case is the independent sample.
- Readings from each blade stay in one split; 302 configurations use five-fold grouped CV.
- Mesh convergence is verified at three densities; Mechanical and APDL agree to the reported precision.
- Limitation: the held-out results informed development, so this was not a fully untouched test set.

### Data structure and train-test split

**615 blade cases × 90 correlated readings = 55,350 observations | split by case, never by individual reading**

| 515 | 100 | 302 | 5 |
|---|---|---|---|
| valid crack cases | healthy cases | classifier configs | grouped CV folds |

## 4 RESULTS & DISCUSSION

**Detection is reliable when the signal-to-noise ratio is high enough, but the available frequency features do not support precise crack sizing.**

| 0.131% | 87.6% | 53.8% | 0.04-0.14 |
|---|---|---|---|
| median crack signature | prediction-averaged BA at 0.1% noise | prediction-averaged BA at 1.0% noise | sizing $R^2$ |

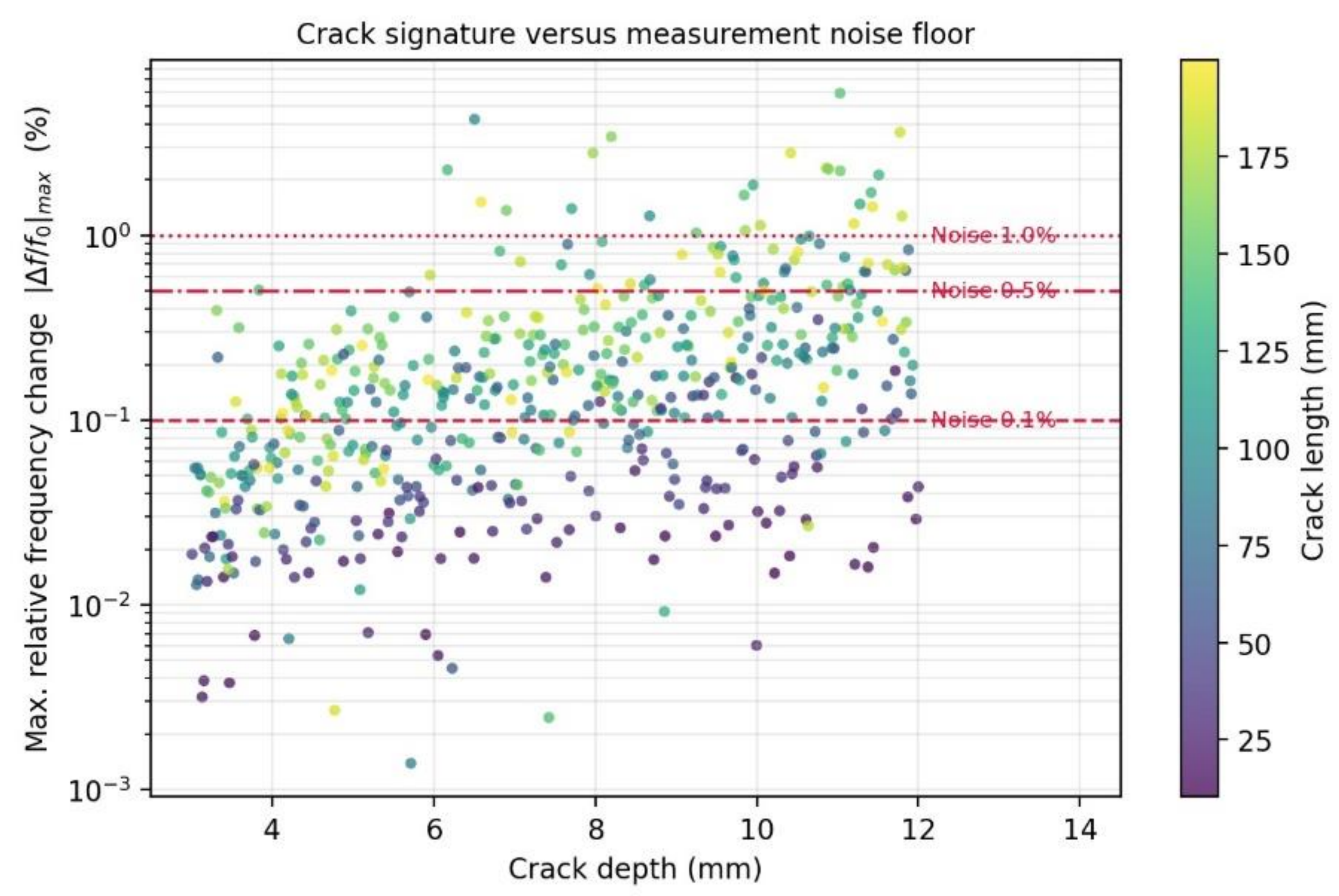
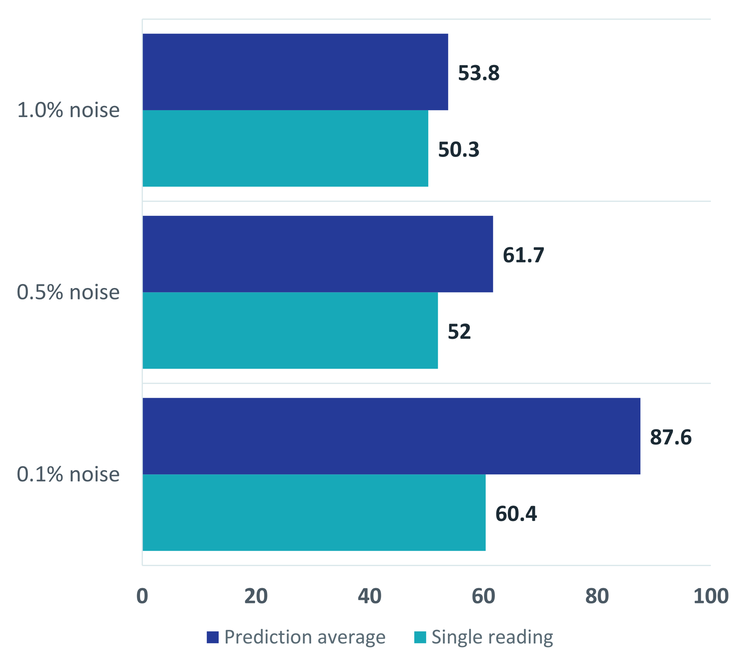


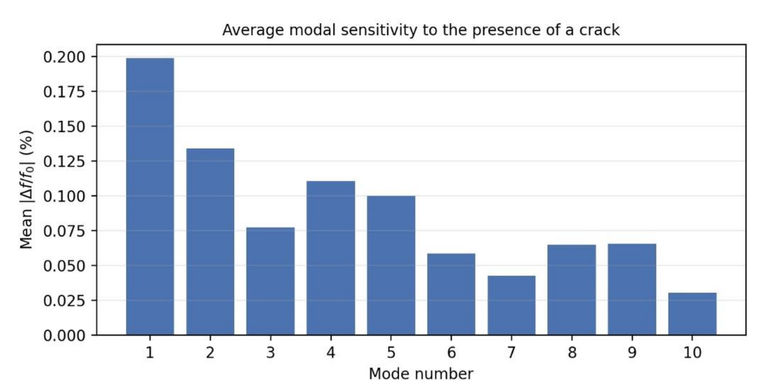

*Figure 1. The median crack signature is 0.131%, so many cases lie close to or below realistic measurement-noise levels.*

### Accuracy falls as noise increases




**Prediction averaging performs best at every tested noise level, although accuracy still drops sharply as the noise increases.**

### Detection works; sizing remains weak




- Aggregating readings raises balanced accuracy from 56.2% to 86.6% and healthy-blade identification from 17.4% to 80.0%.
- Case-level crack recall remains high at 93.2%.
- Feature averaging works best for sizing: lowest MAE in 12/12 comparisons and highest $R^2$ in 11/12.
- Length and depth estimates fail when test values fall outside the training range.

**Recommended use: collect repeated readings, average predictions for crack detection, average frequency features for sizing, and calibrate the threshold for each noise level.**

## 5 CONCLUSION & FUTURE WORK

### Conclusion

- Cracks can be detected when the measurements have sufficient SNR and repeated readings are available.
- Prediction averaging improves healthy-blade recognition while keeping crack recall at 93.2%.
- Crack sizing is still too uncertain for deployment.

### Future work

- Validate modal predictions on a physical blade.
- Compare smeared, discrete and breathing models.
- Include rotational prestress and full-disc cyclic coupling.
- Add mode shapes, curvature and richer sensing features.
- Expand healthy blades and crack severities.

**Crack detection is promising, but reliable sizing needs richer measurements.**

**Practical use should be limited to repeated, low-noise measurements until the method has been validated experimentally.**

## 6 REFERENCES & ACKNOWLEDGMENTS

Selected references

[4] Yang et al., Engineering Failure Analysis, 2025.
[10] Henderson et al., Sensors, 2024.
[11] Gillich et al., Sensors, 2022.
[17] Breiman, Machine Learning, 2001.
[18] Pedregosa et al., JMLR, 2011.

Acknowledgments

We thank Dr. Bùi Quang Thành for his guidance and acknowledge the support of USTH's Department of Technology and Engineering and the Center for Innovation and Entrepreneurship.