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Noise Filtering and Wavelet Analysis for Damaged Flight Recorder Data

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Abstract

Flight recorder data provide the most reliable source of evidence for reconstructing aircraft accidents, evaluating system performance, and improving aviation safety. The integrity of Flight Data Recorder (FDR) and Cockpit Voice Recorder (CVR) recordings frequently becomes compromised by severe impact forces, fire exposure, underwater immersion, electromagnetic interference, and storage media degradation, resulting in noise contamination, missing observations, and signal distortion. Accurate recovery of damaged recordings therefore requires advanced signal processing techniques capable of preserving safety-critical information while minimizing reconstruction errors. This chapter presents a comprehensive review of noise filtering and wavelet analysis techniques for damaged flight recorder data, covering the architecture of modern flight recorder systems, characteristics of degraded aviation signals, conventional digital filtering methods, adaptive filtering algorithms, and multi-resolution wavelet-based denoising strategies. Hybrid signal restoration frameworks integrating wavelet transforms with machine learning and deep learning models are examined to highlight recent advances in intelligent aviation signal processing. Performance evaluation metrics, feature extraction methods, and practical applications in aircraft accident investigation are also discussed to assess reconstruction accuracy and operational reliability. Current research challenges, including computational complexity, mixed-noise environments, incomplete data recovery, and the lack of standardized benchmark datasets, are critically analyzed. The chapter concludes by outlining future research directions involving explainable artificial intelligence, edge computing, digital twins, and adaptive wavelet frameworks for resilient, high-accuracy flight recorder signal restoration, thereby contributing to the advancement of intelligent aviation safety and accident investigation technologies.

Keywords: Flight Data Recorder (FDR), Cockpit Voice Recorder (CVR), Wavelet Transform, Noise Filtering, Signal Restoration, Aircraft Accident Investigation.

Introduction

The aviation industry has undergone a profound technological transformation with the adoption of advanced avionics, intelligent flight control systems, integrated sensor networks, and digital communication architectures that continuously monitor every aspect of aircraft operation [1].

Modern commercial and military aircraft generate vast quantities of operational data through thousands of interconnected sensors responsible for measuring flight dynamics, engine performance, environmental conditions, navigation status, structural responses, and pilot control actions [2]. These continuously recorded measurements provide an accurate representation of aircraft behavior throughout all phases of flight, enabling engineers, investigators, manufacturers, and regulatory authorities to evaluate operational performance with exceptional precision [3]. The increasing complexity of aircraft systems has elevated the importance of reliable data acquisition and preservation because operational decisions, maintenance strategies, safety improvements, and accident investigations depend upon the availability of authentic flight information [4]. Flight recorder technologies therefore occupy a central position within the global aviation safety framework by providing objective evidence that supports systematic analysis of aircraft performance under both routine operating conditions and emergency situations [5].

Flight Data Recorders (FDRs) and Cockpit Voice Recorders (CVRs) constitute the primary repositories of operational information collected during flight missions [6]. Flight Data Recorders continuously capture hundreds or thousands of parameters describing aircraft altitude, airspeed, engine operating conditions, control surface movements, fuel consumption, hydraulic pressure, navigation variables, acceleration, and numerous additional measurements that collectively characterize aircraft performance [7]. Cockpit Voice Recorders complement these quantitative observations by preserving pilot communications, crew coordination, warning alerts, radio transmissions, and ambient cockpit sounds, thereby providing valuable contextual information regarding operational decision-making and human interaction with aircraft systems [8]. Synchronization between numerical flight parameters and cockpit audio enables comprehensive reconstruction of accident sequences through correlation of technical system behavior with pilot responses and environmental influences [9]. The combination of these complementary recording systems provides investigators with a complete operational history capable of supporting accurate accident analysis, engineering validation, and continuous enhancement of aviation safety standards [10].