AM-FM Decomposition Applications in Cardiovascular Imaging and Analysis: A Review

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Abstract. This review explores the application of Amplitude Modulation-Frequency Modulation (AM-FM) decomposition in cardiovascular imaging. AM-FM decomposition enables the extraction of local amplitude and frequency information from medical images, enhancing the detection of subtle structural and textural changes critical for early cardiovascular disease (CVD) diagnosis. Key applications include carotid intima-media thickness (IMT) analysis, atherosclerotic plaque classification, microvascular flow dynamics assessment, and myocardial infarction quantification. We discuss the benefits and limitations of AM-FM decomposition in clinical diagnostics and the potential integration of artificial intelligence (AI) to improve efficiency and diagnostic precision. The findings suggest that AM-FM decomposition, particularly when combined with AI, could significantly advance the early detection and management of CVDs.

Keywords: AM-FM decomposition, cardiovascular imaging, carotid intima-media, atherosclerotic plaque classification, artificial intelligence.

1. Introduction

Cardiovascular diseases (CVDs) remain one of the primary causes of death globally, accounting for about 32% of deaths worldwide each year. Conditions like coronary heart disease, stroke, and peripheral arterial disease present significant clinical challenges, with early detection and effective treatment being critical to reducing patient morbidity and mortality [1]. Traditional imaging methods, such as ultrasound, CT, and MRI, are vital for diagnosing CVDs, but they have limitations in offering quantitative data and detecting subtle early-stage changes. To overcome these issues, combining advanced computational techniques, including AI and signal processing, has shown promise in improving diagnostic accuracy and patient care [2].

One of the most effective computational techniques in this area is Amplitude Modulation-Frequency Modulation (AM-FM) decomposition. This approach breaks down a signal into its local amplitude and frequency components, allowing for multi-scale feature extraction. Unlike standard Fourier analysis, which focuses on global frequency content, AM-FM can capture localized signal variations, making it particularly useful for analyzing texture and dynamic changes in medical images [3]. This is especially relevant for cardiovascular imaging, where small structural changes can indicate the early stages of disease progression.

Recently, AM-FM decomposition has found applications across various medical imaging fields, including the analysis of brain, liver, and lung tissues. Its capacity to detect dynamic changes and analyze textural details has proven useful for diagnosing pathological conditions in these areas [4]. In cardiovascular imaging, the technique has been used to assess structural alterations in the carotid arteries and myocardium. For example, it can measure intima-media thickness (IMT) in the carotid arteries, an important marker for atherosclerosis, providing more detailed information than traditional imaging methods [5]. Furthermore, AM-FM has been utilized to classify atherosclerotic plaques based on their texture, aiding in the prediction of plaque rupture risks and related cardiovascular events [6].

This review aims to explore the use of AM-FM decomposition in cardiovascular imaging, focusing on applications such as IMT analysis, plaque classification, microvascular flow analysis, and myocardial infarction quantification. We will assess the strengths and limitations of the technique, including its sensitivity to noise and computational demands, and consider how it could evolve in clinical diagnostics. Looking to the future, AM-FM decomposition, especially when paired with AI, holds significant potential for enhancing the early detection and treatment of cardiovascular diseases.

2. AM-FM Decomposition: Basic Principles

Amplitude Modulation-Frequency Modulation (AM-FM) decomposition is widely used in medical imaging due to its capability of analyzing spatial variations across multiple scales, revealing intricate textures that can be diagnostically significant [2]. In this method, an image is represented by local amplitude and frequency components, enabling the extraction of fine details that are otherwise challenging to observe. AM-FM decomposition separates images into amplitude and phase components, where the local frequency, representing tissue changes, is derived from the phase gradient.

This decomposition approach utilizes Gabor filters and Hilbert transforms to isolate frequency variations at multiple scales, allowing a more nuanced view of textures in medical images [3]. Unlike traditional Fourier analysis, which focuses on static frequency components, AM-FM can adapt to changes in structure and intensity across spatial variations. This adaptability is especially useful in cardiovascular imaging, where even minor variations in tissue texture and structure can indicate potential pathology. By breaking down the image into these frequency-modulated elements, AM-FM enables highly sensitive diagnostics in areas like early plaque development and microvascular health.

2.1. The mathematical basis of AM-FM decomposition

The mathematical basis of AM-FM decomposition involves representing an image I(x, y) as a product of local amplitude a(x, y) and phase components. The decomposition can be expressed as:

$$I(x,y) = a(x,y)\cos\big(\emptyset(x,y)\big) \tag{1}$$

Here, $a(x,y)$ denotes the local amplitude, capturing the intensity variations in the image, and $\emptyset(x,y)$ is the phase function that encodes the texture and structural information. The local frequency $f(x,y)$, which provides insight into tissue changes, is derived from the phase gradient:

$$f(x,y) = \nabla\emptyset(x,y) \tag{2}$$

This local frequency describes the rate of change in texture and reveals diagnostic features. The process typically employs Gabor filters and Hilbert transform to isolate multi-scale frequency variations, offering a dynamic and detailed view of image textures. AM-FM decomposition adapts to spatial variations, allowing for the identification of subtle diagnostic indicators in areas like cardiovascular imaging.

2.2. Implementation for AM-FM Decomposition

In medical imaging, AM-FM decomposition is an important technique that can be effectively implemented by combining Gabor filters and the Hilbert transform. The Gabor filter, due to its advantages in extracting specific textures and directional information, becomes a key tool for capturing frequency components. This filter can highlight significant features in the image, laying the groundwork for subsequent analysis.

After applying the Gabor filter to the medical image, we can utilize the Hilbert transform to calculate local amplitude and frequency. The Hilbert transform generates an analytic signal, allowing us to extract amplitude and phase information, which is crucial for understanding the local features of the image. Through these steps, we can delve into the underlying structures of medical images, thereby enhancing the accuracy of diagnosis and treatment.

We can use Python code to implement this algorithm, which mainly includes the following two steps. (1) Localized amplitudes reflect intensity changes and can be associated with tissue structural changes. (2) Localized frequencies capture the rate of change in texture and help detect early abnormalities such as plaque or microvascular disruption.

This Python-based AM-FM decomposition software provides a practical method for observing textural and structural changes in medical images to support the diagnostic process of cardiovascular imaging.

3. Applications for Cardiovascular Imaging

The application of AM-FM decomposition in cardiovascular imaging represents a significant advancement in the diagnostic capabilities within this field. By focusing on the intricate textural characteristics of cardiovascular tissues, this technique offers a more nuanced understanding of various pathological conditions, such as atherosclerosis and myocardial infarction. Unlike traditional imaging methods, which may overlook subtle changes, AM-FM decomposition excels at revealing hidden patterns that can indicate the risk of severe cardiovascular events. Additionally, its sensitivity to microvascular flow dynamics enables early detection of vascular diseases, which is crucial for timely intervention. Overall, AM-FM decomposition not only enhances the precision of cardiovascular assessments but also paves the way for more personalized treatment approaches, ultimately improving patient outcomes and supporting proactive healthcare strategies.

3.1. Carotid Intima-Media Texture Analysis

In cardiovascular diagnostics, carotid intima-media thickness (IMT) is the primary indicator of early atherosclerosis. Traditional IMT measurements are limited to assessing thickness, and it is often difficult to capture subtle structural changes that may indicate early disease progression. As the prevalence of cardiovascular disease rises, timely and accurate diagnosis has become particularly important.

The literature suggests that by isolating textural changes in the intima-media, AM-FM decomposition provides a more sensitive method of atherosclerosis risk assessment than conventional imaging techniques. Conventional ultrasound imaging and CT scanning techniques often provide information only on the thickness of the intima and midlayer but are unable to reveal early signs of plaque formation or accurately differentiate between healthy and diseased arterial wall tissue. Traditional IMT measurements are limited to thickness evaluation, often missing fine structural changes that indicate early disease progression [4]. In contrast, AM-FM decomposition captures low-frequency texture changes at multiple scales, and this multiscale analysis can reveal early abnormalities in the arterial wall texture, providing deeper insight into underlying lesions. This sensitivity to subtle changes in texture makes AM-FM decomposition a highly sensitive tool that helps physicians monitor the progression of cardiovascular disease and its risk [5].

The strength of AM-FM decomposition lies in its sensitivity to low-frequency texture changes that may reflect early lipid deposition and atherosclerosis. It was noted that as lipids begin to accumulate within the arterial wall, subtle changes will occur in the elasticity and structure of the tissue, and these changes will show up as low-frequency texture changes in the AM-FM-decomposed images. In contrast to thickness measurement alone, this method is able to recognize structural abnormalities before significant thickening has occurred, thus providing early warning when the disease is still in a subclinical stage. This is particularly important for high-risk groups, such as patients with diabetes and hypertension, where atherosclerosis progresses at a faster rate and early diagnosis helps to better manage the condition.

In addition, AM-FM Breakdown not only supports single-session testing, but also offers the advantage of long-term monitoring. This technology can track the progression of atherosclerosis by detecting small changes in the texture of the arterial wall over multiple imaging examinations. This has important implications for assessing the effectiveness of treatment and adjusting therapeutic strategies, such as adjusting drug dosages or changing intervention modalities. Studies have shown that by quantifying textural changes in the intima-media layer of the arteries, AM-FM decomposition can assist physicians in choosing a personalized treatment regimen that can slow the progression of atherosclerosis or reduce the risk of cardiovascular events.

3.2. Atherosclerotic Plaque Classification

Atherosclerosis poses significant health risks as it progresses, often leading to severe cardiovascular events. AM-FM decomposition enhances the classification of plaques into symptomatic and asymptomatic types by providing insights into their textural properties [6]. Unlike standard imaging, which may not capture the complexity of plaque structure, AM-FM allows for precise plaque classification through texture-based analysis.

This technique identifies vulnerable plaques by isolating texture patterns that indicate potential rupture risk, thereby supporting early intervention. When combined with machine learning models, AM-FM features enable risk stratification by accurately differentiating between plaque types [7]. This integration of texture-based classification provides a valuable diagnostic tool for clinicians aiming to identify high-risk patients.

3.3. Microvascular Flow Analysis

Analyzing microvascular flow dynamics is critical for assessing cardiovascular health, as microcirculatory dysfunction can often serve as an early indicator of diseases like diabetes and peripheral artery disease. Detecting these vascular abnormalities early on is crucial since minor changes in microvascular flow may occur well before the appearance of overt symptoms, enabling prompt intervention and potentially mitigating disease progression AM-FM decomposition's sensitivity to subtle frequency changes enables a detailed analysis of flow patterns, capturing minor disruptions that may indicate the onset of vascular issues [8]. This is especially effective in imaging techniques like laser speckle contrast imaging (LSCI), which relies on frequency variations to visualize blood flow. LSCI benefits from AM-FM decomposition's heightened sensitivity to frequency shifts, offering a clearer, more detailed perspective on microvascular dynamics and aiding in the detection of perfusion abnormalities associated with chronic conditions such as diabetes. Research indicates that the combination of LSCI and AM-FM decomposition can enhance diagnostic accuracy and improve monitoring of disease progression by detecting small, otherwise unnoticed flow changes that traditional imaging methods might overlook

Through its detailed analysis, AM-FM decomposition can quantify blood flow changes, offering insights that traditional methods might miss. This non-invasive approach provides valuable data for assessing and monitoring vascular health in patients, contributing to early diagnosis and better disease management [9]. This quantifiable information not only captures previously undetected variations but also offers valuable insights into how vascular health evolves in response to treatments. With ongoing monitoring, clinicians can make well-informed, data-driven adjustments to treatment plans based on the patient's unique vascular responses. As a non-invasive and highly precise approach to microvascular evaluation, AM-FM decomposition supports early diagnosis, facilitates tailored treatment planning, and aids in monitoring treatment effectiveness, thereby contributing to more effective disease management and better patient outcomes. Recent studies have also highlighted the potential of this technology for routine clinical applications, especially if optimized filtering methods and hardware acceleration techniques continue to advance, which will pave the way for wider use of this technology in the real world.

3.4. Quantification of Myocardial Infarction

Myocardial infarction (MI), commonly known as a heart attack, results in permanent damage to heart muscle tissue due to prolonged ischemia. Assessing the extent of tissue damage and infarct size accurately is crucial for evaluating the severity of MI and guiding subsequent treatment strategies. Traditionally, techniques such as late gadolinium enhancement (LGE) in magnetic resonance imaging (MRI) and computed tomography (CT) have been employed to visualize infarcted myocardium. However, these methods may not always capture subtle textural changes within the myocardial tissue that could indicate varying stages of ischemic damage composition provides a refined approach to myocardial infarction assessment by analyzing texture heterogeneity in MRI and CT images. This technique examines variations in amplitude and frequency modulations across image textures, distinguishing between healthy, ischemic, and infarcted myocardial tissues based on subtle textural differences. By capturing small shifts in texture, AM-FM decomposition reveals critical information about tissue condition, aiding in the differentiation of viable, at-risk, and necrotic areas within the myocardium.

AM-FM decomposition enhances MI evaluation by examining texture heterogeneity in MRI and CT images [10]. This method assesses the severity of infarction by analyzing the distribution and intensity of texture changes, which can provide insights into tissue remodeling and healing over time. With its sensitivity to these fine texture variations, AM-FM decomposition supports long-term monitoring, which is essential for tracking changes in myocardial tissue post-infarction. Such ongoing assessment allows clinicians to monitor patients' recovery closely and adapt treatment plans as needed to prevent further complications. This technique distinguishes between healthy, ischemic, and infarcted myocardial tissues by highlighting subtle textural differences that indicate the severity of damage. With its ability to capture multiscale variations, AM-FM decomposition is particularly useful for quantifying the extent of myocardial infarction. The sensitivity of the decomposition to subtle texture variations supports long-term monitoring and helps clinicians design personalized treatment strategies.

Furthermore, AM-FM decomposition facilitates personalized treatment strategies by providing quantitative data that can guide interventions. For instance, the ability to precisely measure infarct size and characterize the nature of the damaged tissue enables clinicians to make data-driven decisions, such as optimizing medication dosages or planning for possible surgical interventions like coronary artery bypass grafting (CABG) or angioplasty. With recent advancements in image processing and hardware acceleration, AM-FM decomposition holds significant potential for routine clinical use, offering a non-invasive, detailed, and quantitative approach to myocardial infarction assessment that complements traditional imaging techniques and enhances clinical decision-making.

4. Advantages and Limitations of AM-FM Decomposition

AM-FM decomposition offers distinct advantages, such as multiscale sensitivity and compatibility with a variety of imaging modalities, which make it a powerful tool for early cardiovascular diagnosis. However, it also has notable limitations, particularly in computational demands and sensitivity to noise AM-FM decomposition offers distinct advantages, such as multiscale sensitivity and compatibility with a variety of imaging modalities, which make it a powerful tool for early cardiovascular diagnosis. AM-FM's ability to detect minute changes in tissue texture provides clinicians with a powerful tool for identifying early-stage cardiovascular diseases. The fine granularity of texture analysis allows for the detection of subtle structural changes in vascular tissues that may not be apparent using traditional imaging methods. The technique's capacity to function across different spatial frequencies allows for the detection of patterns and textures at multiple scales, which is essential for analyzing complex structures such as arterial plaques or myocardial tissues. This multiscale capability makes AM-FM decomposition adaptable to a wide range of cardiovascular imaging challenges.AM-FM decomposition is adaptable to various imaging modalities, such as ultrasound, MRI, and CT, establishing it as a versatile diagnostic tool across multiple clinical settings. Moreover, its non-invasive nature enhances patient comfort while still delivering high diagnostic accuracy.

However, it also has notable limitations, particularly in computational demands and sensitivity to noise. AM-FM decomposition demands considerable computational power, especially for processing large datasets from high-resolution medical images, which may limit its feasibility in real-time clinical settings. Additionally, the technique's sensitivity to noise can introduce inaccuracies in texture analysis, often requiring advanced filtering and regularization techniques to reduce noise and achieve reliable results.

To overcome these limitations, advancements in computation and denoising algorithms are necessary. Further investigation into optimized filtering techniques and hardware acceleration could potentially enable AM-FM for routine clinical application.

5. Prospects for Development and Integration with AI

The integration of AM-FM decomposition with artificial intelligence (AI) has the potential to transform cardiovascular diagnostics. By combining AM-FM features with AI-based classifiers, such as support vector machines (SVMs) or convolutional neural networks (CNNs), the diagnostic accuracy and efficiency of this technique can be significantly enhanced. For example, research indicates that combining AM-FM features with SVM classifiers enables the system to achieve high accuracy in classifying atherosclerotic plaques. This suggests that AI-driven AM-FM analysis could potentially automate plaque classification, reducing the time and effort required by clinicians and improving diagnostic consistency.

An exciting development in this area is wearable AI-driven AM-FM systems, equipped with biosensors that continuously monitor cardiovascular parameters such as heart rate and blood flow. These biosensors rely on AM-FM decomposition to analyze collected data in real-time, enabling personalized, adaptive health monitoring. This technology offers a significant advantage over traditional health-monitoring devices by adapting to individual cardiovascular profiles, making it highly suitable for personalized healthcare management. [10]

Another promising area for AI integration is in the real-time monitoring of cardiovascular health. Future developments may include the application of AM-FM decomposition technology to wearable devices that continuously monitor cardiovascular parameters such as blood flow and tissue texture. By utilizing artificial intelligence algorithms trained on AM-FM features, these devices can send real-time alerts to patients and healthcare providers when abnormal patterns are detected. This integration could pave the way for more personalized and prospective cardiovascular care ultimately reducing the incidence of heart attacks, strokes and other serious complications.

Furthermore, AI-enhanced AM-FM decomposition could be instrumental in advancing precision medicine, where treatments are tailored to the individual based on their specific cardiovascular health profile. Machine learning models could be used to analyze large-scale AM-FM data, identifying patterns that correlate with different stages of disease progression or treatment response. This approach allows clinicians to more accurately predict patient outcomes and tailor treatment strategies using detailed, personalized insights.

As computational power continues to increase and AI algorithms become more sophisticated, the clinical applications of AM-FM decomposition are expected to expand significantly. Future research should focus on optimizing the computational efficiency of AM-FM algorithms, developing robust noise reduction techniques, and exploring new AI-based approaches to enhance the diagnostic and predictive capabilities of this powerful imaging tool.

6. Conclusion

AM-FM decomposition emerges as a transformative technique in cardiovascular imaging, significantly enhancing the capacity for early detection and precise characterization of various cardiovascular diseases. Its ability to analyze local amplitude and frequency components provides insights into the intricate textures of vascular tissues, facilitating improved assessments of conditions such as atherosclerosis and myocardial infarction. The review highlights the method's effectiveness in applications ranging from carotid intima-media thickness analysis to the classification of atherosclerotic plaques, underscoring its diagnostic potential. While challenges such as computational demands and noise sensitivity exist, the promising integration of artificial intelligence offers a pathway to augment the capabilities of AM-FM decomposition, enabling more efficient and accurate diagnostic processes. Looking ahead, the continued refinement of this technology, alongside advancements in AI, positions AM-FM decomposition at the forefront of cardiovascular diagnostics, paving the way for personalized healthcare strategies that could significantly reduce the burden of cardiovascular diseases on patients and healthcare systems alike.

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