A Robust Audio Watermarking Technique for Uncompressed Audio Samples Using SWT-SVD Enhanced with Arnold Transform and Fuzzy Logic

Gerald Jem Bernandino
Department of Electrical Engineering
University of the Philippines Los Baños
Los Baños, Laguna
gabernandino@up.edu.ph

Melvin Ilang-Ilang
Department of Electrical Engineering
University of the Philippines Los Baños
Los Baños, Laguna
mcilangilang3@up.edu.ph

***Abstract*— The widespread availability of digital multimedia creates substantial weaknesses in intellectual property security, including concerns about piracy and unlawful usage. Traditional audio watermarking approaches sometimes suffer from decreased imperceptibility and robustness, particularly when subjected to complicated attacks such as cropping and pitch-invariant transformation. This paper proposes a robust audio watermarking scheme that integrates stationary wavelet transforms (SWT), singular value decomposition (SVD), Arnold Transform, and Fuzzy Logic. The approach employs Sugeno Type-2 Fuzzy Systems for adaptive watermark embedding and Type-1 for accurate extraction. Results demonstrate that this approach enhances robustness against conventional and advanced signal-processing attacks while preserving excellent audio quality. Metrics such as Signal-to-Noise Ratio (SNR), Objective Difference Grade (ODG), Subjective Difference Grade (SDG), Mean Opinion Score (MOS), and Bit Error Rate (BER) validate its effectiveness. This research advances multimedia security, offering a secure, non-intrusive, and efficient solution for intellectual property protection in audio distribution.**

Keywords—digital audio watermarking, stationary wavelength transform, singular value decomposition, arnold transform, fuzzy logic

I. Introduction

Audio watermarking plays a vital role in ensuring the authenticity and ownership of digital audio content across various industries. However, traditional techniques such as the Discrete Wavelet Transform (DWT) and Discrete Cosine Transform (DCT) have demonstrated limitations in robustness against specific attacks, including cropping and pitch-invariant Time Scale Modification (TSM) [1]. As noted in [1], study emphasized that while DWT and DCT perform well under many conditions, they are vulnerable when feature locations are altered, weakening the watermarking process. There was also a study that proposed the use of DWT-SVD combined with the Arnold Transform, which showed promising results against standard attacks but remained susceptible to cropping [2]. Although the Arnold Transform enhances watermark security, it does not fully resolve all vulnerabilities.

Alternatively, integrating fuzzy logic into audio watermarking has been shown to improve robustness [3]. However, this approach is challenged by high computational complexity, limiting its practicality. Therefore, a clear gap remains in the literature for innovative watermarking techniques that provide robustness against various attacks while maintaining computational efficiency. This study addresses this gap by proposing a hybrid approach that combines Stationary Wavelet Transform (SWT), Singular Value Decomposition (SVD), Arnold Transform, and Fuzzy Logic.

II. Related Work

Recent studies have widely applied Fuzzy Logic in image watermarking and data hiding schemes, primarily leveraging human-perceptible characteristics such as luminance, edge, and contrast. These methods commonly employ Mamdani-type Fuzzy Inference Systems (FIS) [4], with Fuzzy Logic primarily used to optimize image scaling factors for balancing imperceptibility and robustness [5]. In most cases, its application is limited to image preparation rather than the embedding or extraction process. However, some approaches utilize Fuzzy Logic to compute similarity matrices, where matrices are segmented based on image gray levels [6].

In contrast, this research explores the use of Fuzzy Logic in audio watermarking, not by representing audio characteristics in linguistic terms, but by focusing on the numerical values of singular values to prioritize accuracy. Sugeno models have been effectively used in applications requiring precise control, such as robotic gripper systems that adaptively adjust force based on tactile feedback for accurate and safe object manipulation [4][7]. Given this emphasis on numerical precision, the Sugeno FIS is deemed more suitable for this research.

III. Audio Watermarking Algorithm

This study proposes three combinations of watermarking methods to evaluate the effects of applying the Arnold Transform and Fuzzy Logic on audio watermarking performance. The first method integrates Stationary Wavelet Transform and Singular Value Decomposition (SWT-SVD) with the Arnold Transform, employing downscaling/upscaling and basic arithmetic operations for watermark embedding and extraction. The second method also utilizes SWT-SVD but excludes Arnold Transform, instead incorporating Fuzzy Logic to adaptively control the embedding and extraction processes. The third method combines both the Arnold Transform and Fuzzy Logic within

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the SWT-SVD framework, aiming to leverage the strengths of both enhancements. These three configurations are used to assess and compare imperceptibility, robustness, and computational efficiency in the watermarking process.

A. Preprocessing

The original 60×60 black and white watermark image was loaded in MATLAB appearing as a 60×60×3 RGB image. It was converted to grayscale then binarized to produce a binary matrix. This binary image was reshaped into an 1800×2 matrix and encoded using a (3,2) binary code scheme, adding redundancy for robustness. A second round of encoding was applied to part of the output, and the result was reshaped into a 120×120 binary-encoded watermark image.

Depending on the method, the image was either directly processed or scrambled using the 2D Arnold Transform (for Method 1 and Method 3) with key iterations of two for added security. All versions then underwent first level 2D SWT using the 'db6' wavelet, yielding four sub-bands. The approximation sub-band cA_{wm} was decomposed using SVD and the singular values S_{wm} were extracted for embedding. The number of singular values matched one less than the total number of audio segments. The detail coefficients sub-bands cH_{wm}, cV_{wm}, and cD_{wm}, along with singular vectors U_{wm} and V_{wm} were stored for extraction. For Methods 2 and 3, the three largest singular values were stored as AddKey1, AddKey2, and AddKey3 for use in the fuzzy logic system. The detailed process flowchart for the preprocessing of the watermark is shown in Fig. 1.

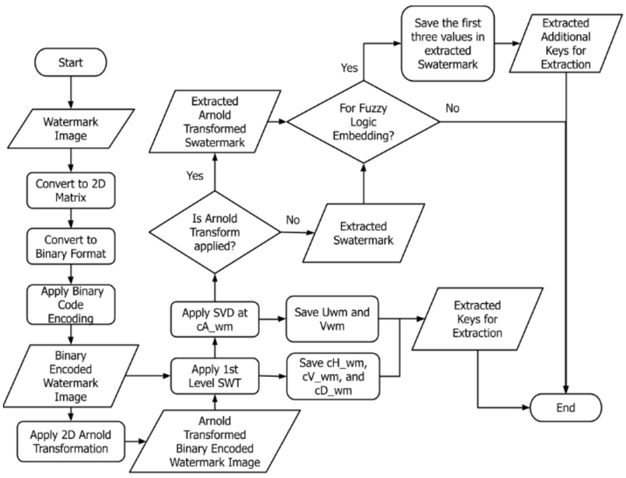


Fig. 1. Flowchart for image watermark preprocessing.

The number of audio segments of the audio samples is calculated using the following formula:

$$numSegments = \frac{AudLen}{sD \times f_s} \quad (1)$$

Where *AudLen* is the length of the audio array, *sD* is the segment duration, and *fs* is the sampling frequency [8].

B. Watermark Embedding

The host audio was divided into 30 blocks, each processed using first level 1D SWT with the 'Haar' wavelet, yielding approximation coefficients cA and detail coefficients cL. Each cA underwent SVD to produce U_{audio}, S_{audio}, and V_{audio} matrices, which were then used for embedding. The embedding rules and set of S_{wm} varied per method. The detailed process flowchart for the watermark embedding process is shown in Fig. 2.

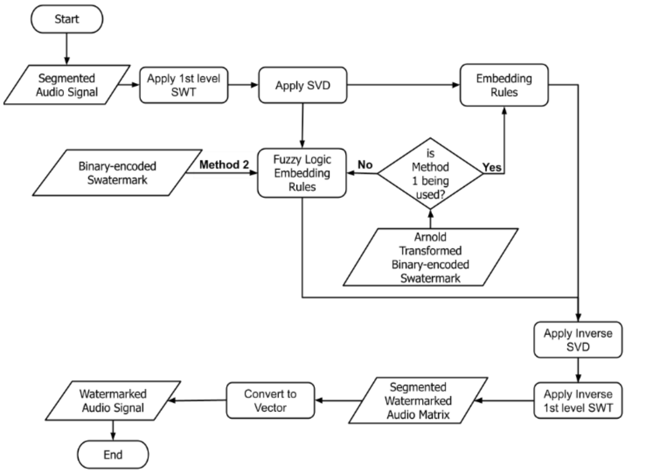


Fig. 2. Flowchart for watermark embedding process.

Method 1 used 29 Arnold Transformed binary-encoded S_{wm} values, scaled by 0.01, and directly added to S_{audio} to form S_{new}. In contrast, Methods 2 and 3 implemented a fuzzy logic-based embedding approach. Method 2 used a binary-encoded S_{wm}, while Method 3 employed its Arnold Transformed version with the same number of S_{wm} values. Both methods utilized MATLAB's Sugeno Type-2 Fuzzy Inference System (FIS), which featured two inputs— S_{audio} and S_{wm} —and one output, S_{new}. The input S_{audio} was modeled using 7 triangular membership functions, while S_{wm} had 4. The output S_{new} was also defined using 7 membership functions. These membership functions were triangular and adaptively distributed across the value range of their respective input arrays.

TABLE I. FUZZY BASED EMBEDDING RULES (SUGENO TYPE-2 FIS)

Rule Number	Input		Output
	S_{audio}	S_{wm}	S_{new}
1	Very Low	Zero or Small or Intermediate or Large	Very LowSmall
2	Low	Zero or Small or Intermediate or Large	LowSmall
3	Moderate Low	Zero or Small or Intermediate or Large	ModerateLow
4	Moderate	Zero or Small or Intermediate or Large	ModerateIntermediate
5	Moderate High	Zero or Small or Intermediate or Large	ModerateHigh
6	High	Zero or Small or Intermediate or Large	HighLarge
7	Very High	Zero or Small or Intermediate or Large	Very HighLarge

The fuzzy logic rules (Rules 1–7) ensured S_{new} remained closely aligned with S_{audio}, introducing minimal changes based on S_{wm}. The S_{new} values were added to Saudio to form Snew.

Regardless of the method, S_{new} underwent inverse SVD using Uaudio and Vaudio, followed by inverse SWT using the original cL. This process produced 30 watermarked audio blocks, which were then concatenated to form the final watermarked audio signal.

C. Watermark Attack Test

To evaluate the robustness of the proposed audio watermarking technique, a series of watermark attack tests were conducted. These tests simulated various real-world distortions by applying both basic and advanced signal processing attacks to the watermarked audio. The goal was to assess the watermark's resilience against common operations that may unintentionally or intentionally alter the signal. The types of attacks considered in this evaluation are summarized in Table I.

TABLE II. AUDIO SIGNAL ATTACK TYPES AND DESCRIPTION

Audio Signal Attacks	Description
Low-pass Filtering	Low-pass filter with a cut-off frequency of 9 kHz
High-pass Filtering	High-pass filter with a cut-off frequency of 100 Hz
MP3 Compression	MPEG 1 Layer III compression (96 kbps)
Noise Addition	Added White Gaussian Noise (10db)
Cropping	Deleted 10% of the sample points
Time Shifting	Expanded duration by 5 %

D. Watermark Extraction Process

Extracting the watermark is done by reversing the process performed during embedding. However, in the case of Methods 2 and 3, which use Sugeno Type-2 FIS for embedding, a different fuzzy-based extraction is employed—specifically, a Sugeno Type-1 FIS, as only integer-valued singular values are required. Experimental results showed that exact recovery of the original S_{wm} values is unnecessary; rather, the extracted values only need to be sufficiently close to the original for successful reconstruction of the watermark image. The detailed process flowchart for watermark extraction is shown in Fig. 3.

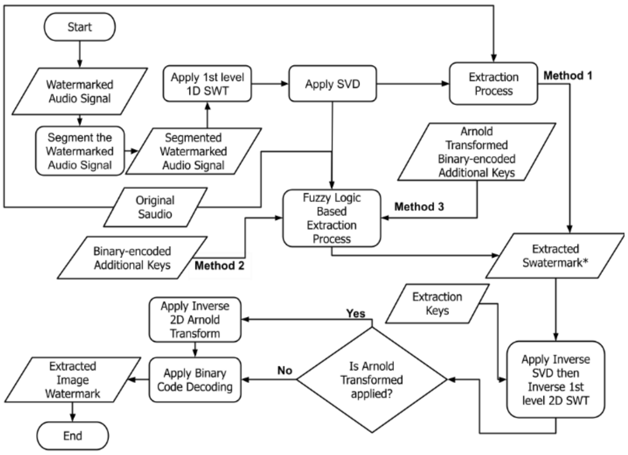


Fig. 3. Flowchart for watermark extraction process.

All methods use S_{new*}, the singular values obtained after applying SWT and SVD to the segmented watermarked audio signal. Method 1 subtracts S_{audio} from S_{new*}, then divides by 0.01 to upscale and obtain $S_{watermark*}$. In contrast, Methods 2 and 3 employ a fuzzy-based extraction process, differing in the values of the additional keys: AddKey1, AddKey2, and AddKey3. These keys are crucial since the parameters of the membership functions are adaptively designed based on their values. Method 2 uses binary-encoded additional keys, while Method 3 uses Arnold-transformed binary-encoded keys.

The Sugeno Type-1 FIS used in the extraction process is designed with two inputs— I_{wm} and S_{mod} —and one output, $S_{watermark*}$. The input I_{wm} indicates the importance of the watermark singular values based on the iteration index, while S_{mod} is the result of subtracting S_{audio} from S_{new*}. The input I_{wm} is modeled with four triangular membership functions, with parameters defined by the additional keys. S_{mod} is modeled with three triangular membership functions that are adaptively distributed due to variation across audio samples. The output $S_{watermark*}$ is modeled with four linear or constant membership functions, whose values are also defined using additional keys.

TABLE III. FUZZY BASED EXTRACTION RULES (SUGENO TYPE-1 FIS)

Rule Number	Input		Output
	I_{wm}	S_{mod}	$S_{watermark*}$
1	MImportant	Little or Medium or Big	High Importance
2	Important	Little or Medium or Big	Medium Importance
3	LImportant	Little or Medium or Big	MediumLow Importance
4	NImportant	Little or Medium or Big	Low Importance

The fuzzy logic-based extraction rules are modeled to produce $S_{watermark*}$ based on I_{wm}, regardless of the intensity of S_{mod}. This principle ensures that the important singular values of the watermark are retrieved. The extracted 30 $S_{watermark*}$ values are used to form an array. From this array, a diagonal matrix is created with the shape 120x120, where the values of the array are placed in the diagonal positions. This matrix now represents S_{wm*}, which is used for inverse SVD along with the original image watermark U_{wm} and V_{wm}, resulting in cA_{wm*}. This is then used for the inverse first level 2D SWT along with the extraction keys cH_{wm}, cV_{wm}, and cD_{wm} using the 'db6' wavelet, yielding the preprocessed watermark image of size 120x120.

For Methods 1 and 3, before binary code decoding, the extracted watermark image matrix underwent the inverse 2D Arnold Transformation with the same iteration count of 2. For Method 2, the process proceeded directly to binary code decoding without applying the Arnold Transformation. The binary code decoding used a codeword length of 3 and a message length of 2 to decode the watermark information. The decoded data was then reconstructed into a 60x60 matrix, successfully recovering the watermark image.

IV. EXPERIMENT RESULTS AND ANALYSIS

A. Watermark Image Preprocessing Results and Analysis

The watermarking methods were evaluated using a 60x60 binary image (Fig. 4(a)). This image underwent preprocessing via binary encoding, producing a 120x120 binary image (Fig. 4(b)), which appears pixelated due to the encoding process. The original pixels were encoded with a (3,2) cyclic code, increasing the image size from 3,600 to 14,400 pixels.

(a) Original Watermark. (b) Binary Encoded Watermark. (c) Arnold Transformed Binary Encoded Watermark.

Fig. 4. Image watermark before and after preprocessing.

For Methods 1 and 3, the image was further processed with an Arnold transform (Fig. 4(c)), rearranging pixel positions while preserving the 120x120 dimensions. Method 2 used the binary encoded watermark without the Arnold transformation. The variation in watermark types results in different singular values in the S_{wm} array, reflected in the additional keys (Table IV).

TABLE IV. ADDITIONAL KEYS USED PER METHOD

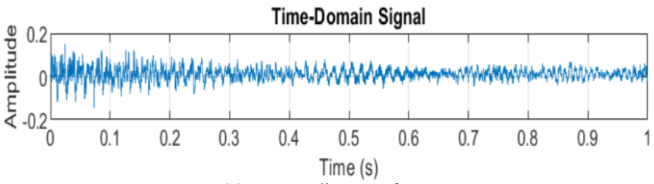
Additional Keys	Methods 1 & 3	Method 2
AddKey1	142.5097	158.5374
AddKey2	27.7530	46.3507
AddKey3	27.0786	19.8320

It is noticeable that the 2-iteration Arnold transformation results in singular values of the watermark image that are generally lower in magnitude and more closely spaced compared to those without the transformation. This behavior can be explained by the nature of the Arnold Transform, which scrambles the spatial distribution of pixel intensities while preserving the overall image energy. By disturbing the localized structure and spreading pixel information across the entire image, the Arnold Transform causes the image's energy—which is typically concentrated in a few dominant singular values—to become more evenly distributed. Consequently, the resulting SVD produces singular values that are lower in peak magnitude and more uniform in scale.

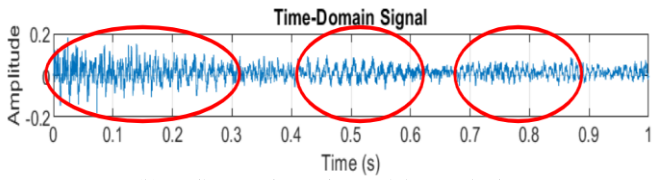
In contrast, the untransformed binary watermark retains its original structure, often containing homogeneous regions or repetitive patterns. These characteristics lead to stronger, more concentrated features that produce higher and more widely spaced singular values during decomposition.

B. *Watermark Embedding Results and Analysis*

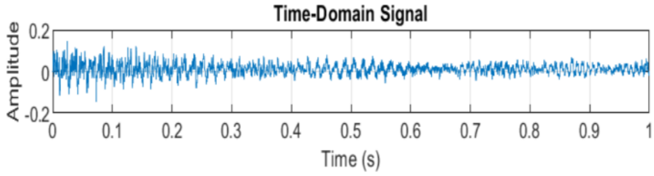
This section experiments with seven audio samples, consisting of five music tracks—classical, electronic, rock, jazz, and pop—and two speech recordings, one male and one female voice. All audio samples are in WAV format, with each music track having a duration of 30 seconds and each speech sample lasting 60 seconds. For the purposes of this discussion, only the results for the classical music sample will be presented. Fig. 5 and Fig. 6 illustrate the waveform of a 1-second part of the audio in the time domain and the low-frequency domain, respectively, before and after the watermark embedding process.



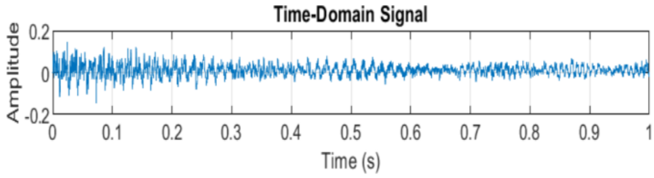
(a) Raw audio waveform.



(b) Audio waveform after applying Method 1.

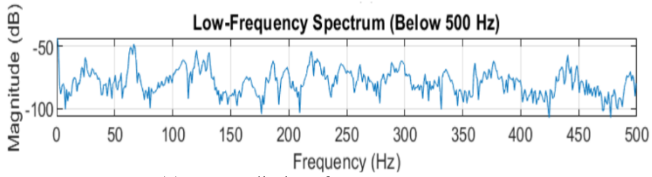


(c) Audio waveform after applying Method 2.

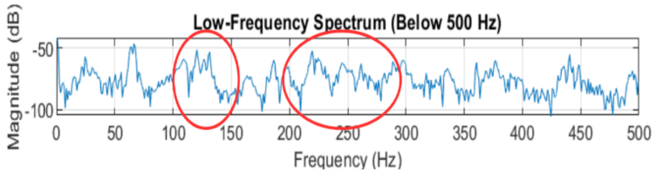


(d) Audio waveform after applying Method 3.

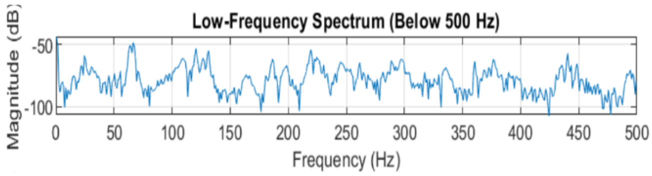
Fig. 5. Time-domain watermark embedding results for a classical music track.



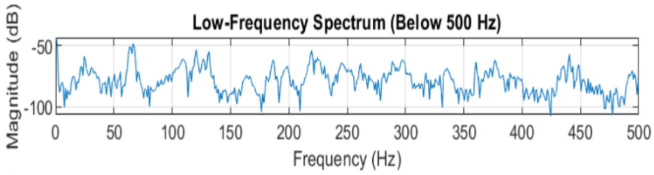
(a) Raw audio low-frequency spectrum .



(b) Audio low-frequency spectrum after applying Method 1.



(c) Audio low-frequency spectrum after applying Method 2.



(d) Audio low-frequency spectrum after applying Method 3.

Fig. 6. Frequency-domain watermark embedding results for a classical music track.

The analysis in this section combines both time-domain and frequency-domain approaches, providing a comprehensive assessment of the watermarking technique's performance across various audio signal characteristics. This dual-domain analysis helps reveal any distortions or alterations introduced during the embedding process that may not be evident when using a single domain alone.

By comparing the raw audio waveform in Fig. 5 with the waveforms from the three methods, Method 1 shows some changes. There are noticeable fluctuations in the amplitude, marked with a red circle. In contrast, Methods 2 and 3 do not show any clear increase in amplitude. A similar pattern is seen in the low-frequency domain in Fig. 6. Method 1 shows a slight increase in magnitude, while Methods 2 and 3 do not show any visible changes to the human eye. This suggests that the methods using fuzzy logic for embedding (Methods 2 and 3) provide better imperceptibility. Similar results are observed across other audio samples, further supporting the effectiveness of fuzzy logic-based methods in maintaining audio transparency.

C. Watermark Attack and Extraction Results and Analysis

(a) Low-pass Filtering. (b) High-pass Filtering.

(c) MP3 Compression. (d) Noise Addition

(e) Cropping Attack. (f) Time Shifting.

Fig. 7. Extraction and post-processed watermark results for watermarked classical audio sample.

After the attack tests were done on the classical audio, the watermark image was extracted after each attack. The results are shown in Fig. 7, where the image on the left is from Method 1, the center image is from Method 2, and the image on the right is from Method 3.

Method 1 lacks robustness against most of the attacks. Except for the low pass filtering attack, the extracted images from the attacked watermarked audio show no resemblance to the original watermark image. Among all the attacks, cropping and time-shifting caused the most damage. In these cases, very few or none of the watermark's singular values were successfully recovered, and the exact pixel positions could not be identified. However, Methods 2 and 3 show strong protection against all the attacks, as the extracted watermark images closely resemble the original watermark image. This also shows that the fuzzy logic-based extraction method is more robust compared to the direct scaling and addition of singular values used in Method 1. Similar results are observed across other audio samples, with Method 1 consistently showing significant degradation in extracted images, though the intensity of alterations varies depending on the sample and the type of attack.

D. Evaluation Metrics Results and Analysis

To further evaluate the performance of the proposed algorithm in terms of imperceptibility and robustness, five metrics were calculated: SNR and ODG for objective imperceptibility analysis; MOS and SDG for subjective imperceptibility analysis; and BER for robustness.

TABLE V. IMPERCEPTIBILITY EVALUATION RESULTS

Evaluation Metrics	Method 1	Method 2	Method 3
SNR	29.29	44.99	49.45
ODG	-0.1407	0.1630	0.1764
MOS	3.88	3.484	3.66
SDG	-0.02	0.02	0.2

The SNR values for all three methods are above the minimum standard of 20 dB set by the International Federation of the Phonographic Industry (IFPI), indicating that all three methods provide good imperceptibility [1]. However, when comparing the methods, it is noticeable that Method 3 delivers the best imperceptibility. This improved performance is due to the use of more closely grouped singular values from the watermark image compared to Method 2. This factor contributes to higher SNR values, even though both Method 2 and Method 3 use fuzzy logic-based embedding. Across all audio samples, similar performance was observed, with variations only in the SNR values; but the same trend holds as Method 3 consistently produced the highest SNR, indicating the best imperceptibility.

TABLE VI. MOS SCALE

Score	Audio Quality
5	Excellent
4	Good
3	Fair
2	Poor
1	Bad

The subjective imperceptibility analysis was conducted using ratings from 50 individuals. They evaluated the audio quality based on the MOS scale shown in Table IV. The ratings for each method were compared to the ratings of the original (raw) audio. From this, both the MOS and SDG values were calculated. The ODG was obtained using the Perceptual Evaluation of Audio Quality (PEAQ) algorithm [9].

The purpose of using both ODG and SDG is to better understand the quality of the audio in terms of measurable values and real listener perception. The values collected were close to 0, which means that all three methods were generally imperceptible. However, the MOS values for all methods fell between "fair" and "good." This was mainly due to the original audio quality itself. Some listeners noticed background noise, which they believed were watermark artifacts, leading to slightly lower ratings.

TABLE VII. ODG AND SDG SCALE

Score	Description
0	Imperceptible
-1	Perceptible but annoying
-2	Slightly annoying
-3	Annoying
-4	Very annoying

Despite this, the low SDG values show that the watermarked audio was rated similarly to the original audio. This means that even though the MOS ratings weren't very high, the three methods still achieved good imperceptibility in their watermark embedding. This observation was also applicable to other audio samples.

TABLE VIII. ROBUSTNESS EVALUATION RESULTS

Audio signal Attacks	BER		
	Method 1	Method 2	Method 3
Low-pass Filtering	0	0	0
High-pass Filtering	1678	0	0
MP3 Lossy Compression	1845	0	0
Noise Addition	207	0	0
Cropping	885	0	0

Audio signal Attacks	BER		
	Method 1	Method 2	Method 3
Time Shifting	984	0	0

The recorded BER values align with the results of the watermark attack analysis. Both show that Method 1 lacks robustness against most types of attacks, except for low-pass filtering. On the other hand, Methods 2 and 3, which use fuzzy logic-based extraction, demonstrate superior robustness. A BER value of 0 indicates that every bit of the original watermark image was perfectly recovered, with no discrepancies. This reflects perfect robustness, meaning the watermark remained completely intact despite the applied attacks. This observation was consistent across other audio samples, although the BER values for Method 1 varied between samples.

E. Computational Complexity

The embedding and extraction processes for all methods were implemented using MATLAB R2024a on a Windows 11 operating system, running on a Ryzen 7 5700X processor with 32 GB of RAM and minimal background processes. The computational time for each method, based on a 30-second classical audio sample, was recorded and presented in Table IX.

TABLE IX. RECORDED PROCESS TIME

Process	Time		
	Method 1	Method 2	Method 3
Embedding Time	0.3316 s	1.1327 s	1.1293 s
Extraction Time	0.2342 s	1.1820 s	1.2145 s

It is evident that Method 1 is the fastest, owing to its straightforward approach. Meanwhile, an increase in processing time is observed when fuzzy logic is incorporated in both the embedding and extraction stages, as seen in Methods 2 and 3. However, this increase in processing time is neither drastic nor problematic, as the recorded durations were all approximately just 1 second.

V. CONCLUSION

This research developed a robust audio watermarking algorithm by evaluating the performance of three methods that incorporate wavelet transformations and fuzzy logic. The proposed algorithm successfully embeds controlled singular values of the watermark image into the unaltered singular values of the audio signal. It is classified as a non-blind watermarking technique, as it requires key information from both the original audio signal and the watermark image during the embedding and extraction phases.

The study also demonstrates that the Arnold Transform contributes not only to robustness but also to the imperceptibility of the watermark. Furthermore, the effectiveness of Sugeno Type-2 Fuzzy Inference System (FIS) in minimizing the distortion introduced by embedding is highlighted, resulting in improved imperceptibility. Meanwhile, the Sugeno Type-1 FIS proved effective in accurately recovering the watermark under various attack conditions, emphasizing the robustness of the algorithm. Importantly, the use of fuzzy logic did not significantly increase computational load, as the additional processing time was minimal.

VI. FUTURE WORK

Exploring blind watermarking, which eliminates dependence on original watermark keys during extraction, can enhance objectivity, security, and robustness. Additionally, applying this method in real-time scenarios such as live streaming is recommended to assess its capabilities in dynamic content protection.

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