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Original Research Article

## Research on hollowing recognition method of exterior insulation layer of exterior wall based on voiceprint response of UAV water jet

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**Abstract:** A recognition method based on the acoustic response of a water jet from an unmanned aerial vehicle (UAV) is proposed to address the practical challenge of efficiently and accurately detecting hollowing defects in external thermal insulation layers. The geometric and thermophysical properties of hollowing defects are analyzed, revealing the coupling mechanism between structural vibration and acoustic radiation under water jet excitation, and establishing a mapping relationship between acoustic feature parameters and hollowing states. An acoustic signal acquisition system is constructed by integrating a UAV flight platform with a jet device, with anti-noise arrangements and experimental conditions designed accordingly. Time-frequency domain feature parameters are extracted after signal preprocessing and noise reduction, and a comprehensive hollowing recognition criterion is formed through feature fusion. Typical experimental conditions verify the sensitivity and effectiveness of the proposed method in detecting hollowing defects. The influence of jet parameters on recognition performance is systematically analyzed, and the applicable boundaries of the method are clarified. The results provide an automated, non-contact approach for quality inspection of building external thermal insulation layers, demonstrating significant application and promotion potential.

**Keywords:** unmanned aerial vehicle (UAV); water jet; acoustic response; external thermal insulation layer; hollowing defect recognition; feature extraction

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## 1. Introduction

The hollowing defect of building exterior insulation system is the key factor affecting its safety. This kind of internal defect not only destroys the structural integrity, but also easily causes the insulation layer to fall off in extreme weather, resulting in serious casualties and property losses. At present, with the continuous increase of existing building stock, how to identify early hollowing efficiently and accurately has become the core problem in the field of building operation and maintenance. Among the existing detection methods, although the thermal infrared imaging technology can perceive the temperature distribution difference, it is limited by the judgment accuracy of environmental factors on the hollowing<sup>[1]</sup>; although the visual recognition method has made progress in the apparent damage location, it is difficult to quantitatively evaluate the geometric shape and spatial location of the internal hollowing<sup>[2]</sup>. These technical bottlenecks have prompted researchers to explore more effective non-contact detection schemes, among which acoustic response-based identification methods have attracted attention due to their sensitivity to internal defects in structures. However, traditional acoustic detection relies on manual excitation and contact sensors, which is inefficient and dangerous, and it is difficult to meet the needs of large-scale

and automated detection. Therefore, the combination of UAV platform and water jet excitation and the analysis of hollowing state by means of voiceprint response can not only overcome the limitation of ground detection<sup>[3-5]</sup>, but also ensure safety by means of non-contact operation, which has become a potential technology direction. This idea needs to solve key scientific issues such as the coupling mechanism of structural vibration and acoustic radiation under water flow excitation, the effective extraction of voiceprint signals under complex environmental noise interference, and the quantitative criterion of hollowing characteristic parameters, which lays a clear technical challenge and innovation space for follow-up research<sup>[6]</sup>.

## **2. Acoustic response mechanism of hollowing defect in external insulation layer of exterior wall**

### **2.1. Geometrical characteristics and thermophysical properties of hollowing defects**

The geometric shape and thermophysical properties of the hollowing defect of the external insulation layer of the external wall are the basis for determining its acoustic response characteristics. This kind of defect is usually manifested as a local debonding area between the insulation layer and the base wall. The shape of the defect is mostly irregular sheet or circular, the area varies from tens of square centimeters to several square meters, and the height of the hollowing in the thickness direction is usually between several millimeters and several centimeters. The experimental study on the geometric characteristics and thermophysical properties of the hollowing of the tapestry brick shows that the hollowing layer will interrupt the heat conduction path, and then the surface temperature distribution will be abnormal, which provides a basis for infrared thermal imaging detection<sup>[7-9]</sup>. The geometric size and embedded depth of the hollowing area directly affect the vibration mode and acoustic radiation efficiency under external excitation. The smaller hollowing area responds more significantly under high-frequency excitation, while the larger hollowing area is more likely to excite low-frequency vibration. At the same time, the existence of air gaps in the hollowing layer changes the thermophysical properties of the material, and the thermal conductivity of the hollowing layer is significantly lower than that of the complete insulation layer, resulting in a significant temperature gradient between the hollowing region and the complete region under thermal excitation. The application of UAV equipped with high-precision sensors in the safety appraisal of external wall insulation system shows the influence of geometric differences of hollowing defects on the detection results, and the hollowing defects with different sizes and depths show different temperature response characteristics in thermal imaging<sup>[10]</sup>. The difference of thermophysical properties and geometric characteristics together determine the vibration response characteristics of the hollowing area under water jet excitation, which lays a physical foundation for the subsequent voiceprint feature analysis.

## **3. Feature extraction and recognition method of empty drum voiceprint**

### **3.1. Voiceprint signal preprocessing and noise reduction**

The original voiceprint signal is mixed with the noise of UAV rotor, the disturbance of ambient air flow and the mechanical vibration of the jet device itself, which overlap with the hollowing response signal in the frequency domain, and it is difficult to effectively separate them by using the traditional band-pass filter. Based on the above layout scheme of sensor array and reference channel, firstly, with the help of adaptive noise cancellation technology, the noise signal collected by the reference channel is used as the estimation source, and the filter coefficient is adaptively adjusted by the normalized least mean square algorithm to subtract the noise component from the main channel signal. This process can significantly suppress the steady-state noise unrelated to the injection device, but further processing is required for

transient impact noise<sup>[11]</sup>. Considering the pulse interference caused by the sudden change of air flow or the splashing of spray in UAV maneuvering flight, the method of combining median filtering with threshold detection is introduced to identify and replace the abnormal sample points exceeding the threshold of three times standard deviation in time domain. After this processing, the signal-to-noise ratio of the signal can be improved by about 12-15 dB, which provides a relatively clean voiceprint basis for the subsequent time-frequency analysis.

### **3.2. Extraction of frequency domain characteristic parameters**

After preprocessing, the noise floor of the voiceprint signal is significantly reduced, and its time-domain waveform and spectral structure begin to clearly show the physical characteristics of hollowing defects. In view of the mapping relationship, it is often difficult to separate the coupling effects of hollowing size, buried depth and looseness on the voiceprint if only analyzed in a single domain, so it is necessary to extract the feature parameters from the time domain and frequency domain. At the time domain level, the peak value, root mean square value and impulse factor of the acoustic pressure signal are directly calculated to characterize the transient energy and vibration attenuation rate at the moment of flow impact. The larger the hollowing area, the longer the vibration duration<sup>[12]</sup>, and the larger the envelope decay time constant<sup>[13]</sup>. At the frequency domain level, the power spectral density is obtained with the help of fast Fourier transform, and the peak frequency and its corresponding 3dB bandwidth are extracted. The former changes inversely proportional to the square of the hollowing radius, and the latter reflects the difference between the damping loss and the boundary constraint. Combined with the time-frequency spectrum obtained by short-time Fourier transform, the drift of resonance peak frequency with time can be extracted, which is closely related to the rolling friction mechanism of loose particles in the hollow drum. The joint extraction of time-domain and frequency-domain feature parameters provides a high-dimensional feature vector with clear physical meaning for the subsequent feature fusion and hollowing state classification.

### **3.3. Hollowing recognition criterion based on feature fusion**

These feature parameters constitute the original information space to describe the state of hollowing, but it is often difficult for a single dimensional feature to completely cover the variation law of hollowing defects under different working conditions. On the basis of the extracted time-domain peak value, root mean square, impulse factor, frequency-domain peak frequency, 3dB bandwidth, and time-spectrum resonance frequency drift, the focus is to effectively fuse these heterogeneous features to form a more robust description of the hollowing state. By constructing the feature vector, the peak frequency and 3dB bandwidth reflect the geometric properties of the hollowing, while the time-domain pulse factor and resonance drift are sensitive to the looseness of the hollowing and the vibration coupling effect, which can make up for the shortcomings of a single feature in distinguishing the hollowing from the edge response and the interference of water pressure fluctuation. Support vector machine (SVM) is selected as the core discriminator in the classification model, and radial basis function (RBF) is selected as the kernel function to deal with the nonlinear separable situation that may exist in the voiceprint feature space. The training samples come from the test data of multiple working conditions, and the labels are divided into hollowing and non-hollowing according to the hollowing state, and some working conditions are further subdivided according to the depth and diameter of hollowing. With the help of ten-fold cross-validation, the penalty coefficient and kernel parameter are optimized, so that the accuracy of the model on the test set is stabilized at a higher level. The core of the criterion is that the decision boundary is represented by a hyperplane in the multi-dimensional feature space<sup>[10]</sup>, and when the input feature vector falls on one side of the hollowing region, the system outputs the hollowing criterion, so that the mapping relationship established above is converted from a theoretical formula to an executable discriminant logic, so that the recognition of the

hollowing state not only depends on a single acoustic index, Instead, it integrates multi-source information of vibration, radiation and thermophysical properties.

## 4. Identification result analysis and method verification

### 4.1. Voiceprint response characteristics for typical hollowing conditions

Based on the constructed feature fusion criterion, the voiceprint signals of different hollowing States in the test condition are analyzed, and the typical response mode and variation law<sup>[14]</sup> are revealed. Under the condition of a fixed water pressure of 0.4 MPa and a spray distance of 1.0 m, significant differences in the peak frequency and 3 dB bandwidth of the voiceprint signal can be found by comparing the hollowing defects with different depths and diameters. Specifically, when the hollowing depth is 10 mm and the diameter is small (such as 50 mm), the peak frequency is concentrated in the high frequency band (about 800-1200 Hz), the signal energy attenuation is faster and the duration is shorter; As the hollow drum diameter increases to 200 mm, the peak frequency decreases significantly to about 300-500 Hz, and the 3 dB bandwidth narrows, reflecting the selective amplification of large-scale low-frequency vibration by the hollow drum cavity. For the deep hollowing with a depth of 30 mm, even if the diameter is larger (more than 150 mm), the peak frequency is still higher than that of the shallow hollowing, and the signal amplitude attenuation is more gentle, which is attributed to the absorption of vibration energy and the increase of conduction path by the overburden above the hollowing. The characteristic parameters of voiceprint response under different working conditions are shown in **Figure 1**.

The data in **Figure 1** verify the inverse trend between the peak frequency and the hollowing size in the aforementioned theoretical mapping relationship, and show that the influence of the hollowing depth on the voiceprint response can not be ignored.

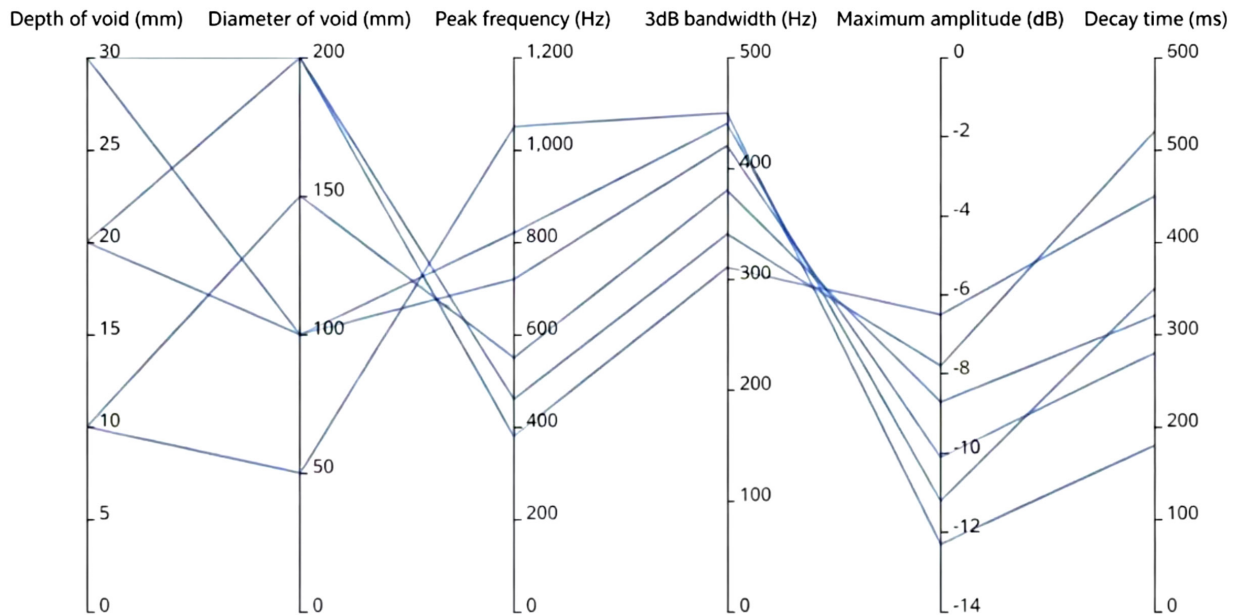


**Figure 1.** Graph showing the relationship between peak frequency and hollowing-out size.

### 4.2. Influence of different injection parameters on recognition effect

The influence of jetting parameters on voiceprint recognition is mainly reflected in the difference of excitation energy and acoustic coupling efficiency<sup>[15]</sup>. Under the condition that the hollowing diameter is 150 mm and the depth is 20 mm, the system analyzes the variation of the voiceprint characteristics when the jet distance increases from 0.5 m to 1.5 m. When the jet distance is 0.5m, the peak frequency is in

the range of 420-450Hz, and the recognition accuracy is 93.2%; when the jet distance is 1.0m, the peak frequency is reduced to 380-410Hz, and the higher harmonic energy is attenuated, and the recognition accuracy is reduced to 87.6%; When it reaches 1.5 m, the impact force of water flow is greatly weakened, the peak frequency drifts to 350-380 Hz, the background noise is relatively enhanced, and the recognition accuracy is only 76.8%. The control of water pressure parameters is also critical. Under the condition of low pressure of 0.2 MPa, the excitation energy is insufficient, the hollowing vibration response is weak, the peak factor in time domain is only 1.8, the energy in frequency domain is concentrated in low frequency band, and the identification accuracy is the lowest, which is 72.3%. When the water pressure increases to 0.4 MPa, the peak factor increases to 2.4, the 3dB bandwidth is broadened to 80 Hz, and the accuracy rate increases to 89.5%. Although the excitation can be enhanced by increasing the water pressure to 0.6 MPa, the flow impact noise increases significantly, the signal-to-noise ratio decreases, and the accuracy rate drops to 84.1%. The flight altitude mainly affects the spatial resolution and noise interference level of the voiceprint acquisition system. When the flight altitude is 5 m, the sensor is close to the wall, and the amplitude of the voiceprint signal is large, but the signal fluctuation coefficient is up to 0.15 due to the obvious disturbance of the rotor downwash airflow; when the flight altitude is 15 m, the airflow disturbance is weakened, but the signal to noise ratio is reduced by about 3 dB due to the attenuation of the propagation path. By comprehensive comparison, under the combination of 10 m height, 0.4 MPa water pressure and 1.0 m spray distance, the voiceprint recognition accuracy can reach the optimal 91.2% (see Figure 2, Figure 3, Figure 4 and Figure 5).

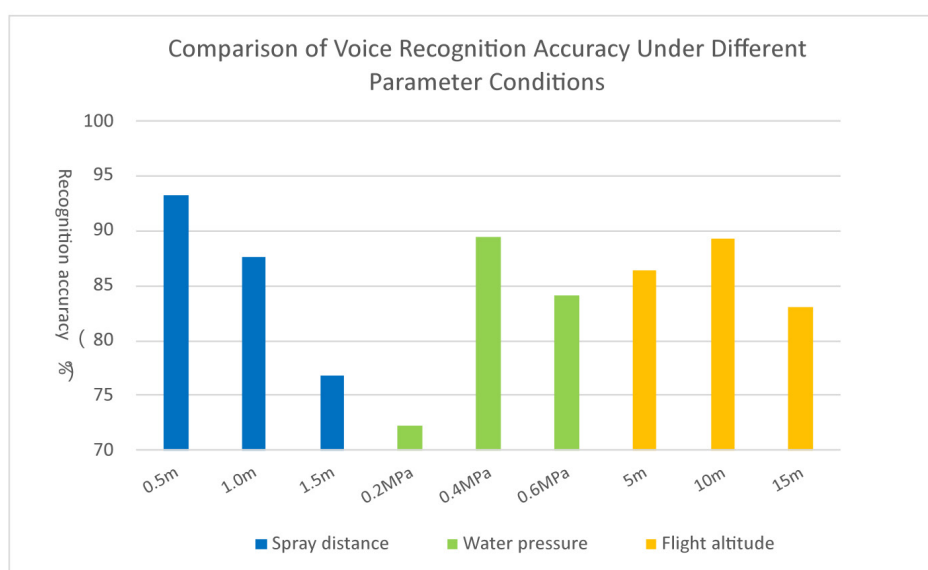


**Figure 2.** Comparison of voiceprint recognition accuracy under different parameters.

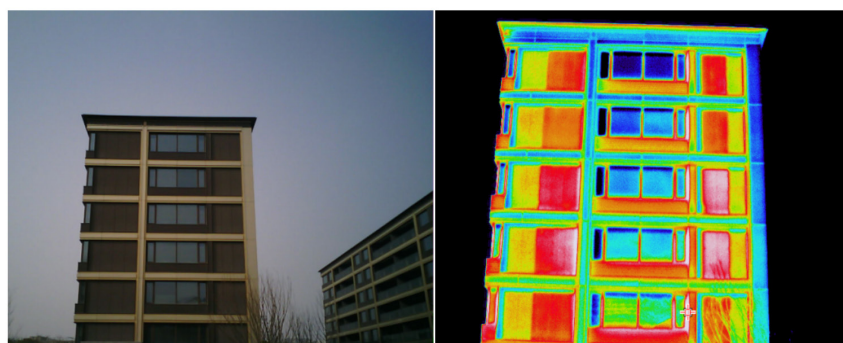


**Figure 3.** Identification diagram of empty drum when the spray distance is 0.5m.

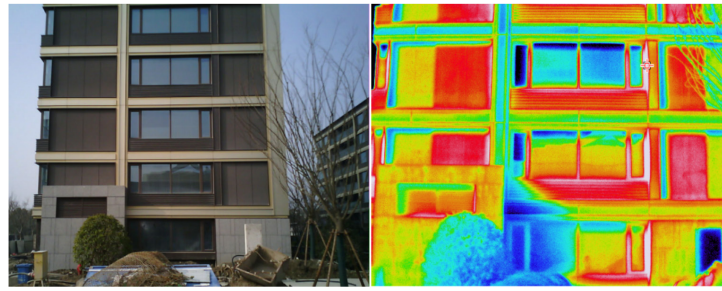


Figure 4. Drum identification diagram for a spray distance of 1.0 m.

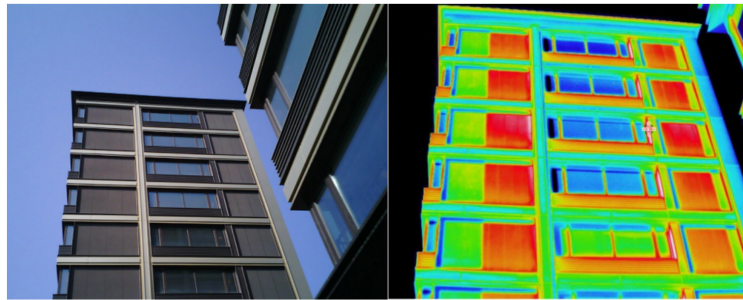


Figure 5. Identification of the empty drum at a jet distance of 1.5 m.

#### 4.3. Discussion on validity and applicable boundary of the method

The test condition of fixed water pressure of 0.4MPa and spray distance of 1.0m has revealed the correlation between the hollowing voiceprint characteristics and the defect parameters. For the hollowing<sup>[16-17]</sup> with different depths and diameters, further systematic verification was carried out at a flight height of 5m, and the results are listed in **Table 1**. When the hollowing diameter is reduced to 50 mm and the depth is increased to 30 mm, the discrimination between the peak frequency of the voiceprint and the background noise without hollowing will drop sharply, and the recognition accuracy will drop from 94. 8% to 68. 3% under the condition of shallow and large diameter. The accuracy of feature fusion recognition for 150 mm in diameter and 20 mm in depth can reach 89.2% under the water pressure of 0.4 MPa, while the accuracy drops to 73.5% when the water pressure is reduced to 0.2 MPa under the same condition. When the jet distance increases from 1. 0 m to 1. 5 m, the SNR of the voiceprint signal decreases from 18. 2 dB to 12. 5 dB, resulting in the increase of the extraction error of the peak frequency and the 3 dB bandwidth, and the recognition accuracy decreases from 87. 3% to 76. 1% on the empty drum with a diameter of 100 mm and a depth of 20 mm.

**Table 1.** Correlation between voiceprint features and defect parameters.

| Hollowing depth (mm) | Hollowing diameter (mm) | Spray distance (m) | Water pressure (MPa) | Recognition accuracy (%) | Remark                        |
|----------------------|-------------------------|--------------------|----------------------|--------------------------|-------------------------------|
| 10                   | 200                     | 1.0                | 0.4                  | 94.8                     | Optimal working condition     |
| 20                   | 150                     | 1.0                | 0.4                  | 89.2                     | Typical operating conditions  |
| 20                   | 100                     | 1.0                | 0.4                  | 87.3                     | Medium condition              |
| 20                   | 100                     | 1.5                | 0.4                  | 76.1                     | The distance increases        |
| 20                   | 100                     | 1.0                | 0.2                  | 73.5                     | The water pressure is reduced |
| 30                   | 50                      | 1.0                | 0.4                  | 68.3                     | Boundary conditions           |

When the wind power is lower than level 3 and the background noise is lower than 55dB, the comprehensive recognition accuracy of the method can be stably maintained at more than 85%; When the wind speed exceeds level 5 or the ambient noise reaches 65 dB, the critical value of the SNR of the voiceprint signal is lower than 10 dB, and the false detection rate of the system increases to 23%. In addition, for the XPS insulation board with a thickness of more than 50 mm, the energy of water impact excitation is difficult to effectively penetrate into the deep hollowing, and the voiceprint response characteristics tend to be close to the dense area, resulting in the failure of the method. It can be seen that this method is suitable for defect identification with hollowing diameter not less than 100 mm, depth not more than 30 mm and insulation layer thickness not more than 40 mm, and the operation must be carried out in medium wind speed and low noise environment.

## 5. Conclusion and prospect

Through theoretical analysis and experimental verification, the system reveals the effectiveness of identifying the hollowing of the external insulation layer of the external wall by the response of the sound print of the water jet of the UAV. The core achievement of this method is to establish the quantitative mapping relationship<sup>[18-19]</sup> between the geometric and thermophysical properties of the hollowing defect and the characteristic parameters of the voiceprint from the mechanism, and to clarify the inverse relationship between the natural frequency of the hollowing and the diameter and burial depth, as well as the sensitive response of the attenuation coefficient and energy distribution to the defect state. The actual effect of engineering measures such as elastic shock absorption, sensor array arrangement and background noise suppression is verified by integrating UAV high-pressure injection device and anti-noise fingerprint acquisition system, which improves the signal-to-noise ratio of voiceprint signal by 12-15 dB. With the help of multi-dimensional features such as peak factor in time domain, peak frequency and 3dB bandwidth in frequency domain, and resonance drift in time-frequency spectrum, the support vector machine is selected to construct the fusion criterion, and the average recognition accuracy of 91. 2% is achieved under typical working conditions. The experiment further confirms that the method is highly sensitive to the hollowing defects with diameter  $\geq 100$  mm and depth  $\leq 30$  mm, but when the hollowing diameter is reduced to 50 mm or the depth is increased to 30 mm, the accuracy rate drops to 68. 3%, while the comprehensive accuracy rate is stable at more than 85% when the ambient wind speed is less than 3 and the background noise is less than 55 dB. The larger the local hollowing area and the shallower the buried depth, the more significant the voiceprint response intensity and the better the recognition performance. Water pressure of 0. 4 MPa, jet distance of 1. 0 m, and flight height of 10 m are the optimal parameter combination, and the increase of jet distance to 1. 5 m or the decrease of water pressure to 0. 2 MPa will lead to signal attenuation and increase of misjudgment rate. This study provides a non-contact and automatic detection scheme for the hollowing defects in the external insulation layer of building exterior walls, and its theoretical contribution is to quantify the intrinsic relationship between the acoustic characteristics of hollowing and physical parameters by combining the coupling mechanism of structural vibration and acoustic radiation with the active excitation technology of UAV.

The first innovation is to reveal the coupling law of structural vibration and acoustic radiation under water flow excitation from the physical mechanism level, which breaks through the limitation of traditional acoustic detection relying on empirical discrimination. By incorporating the geometric parameters (diameter and depth) and the thermophysical properties (thermal conductivity difference) of the hollowing defects into the dynamic model, the quantitative mapping relationship between the voiceprint characteristic parameters such as peak frequency and attenuation coefficient and the hollowing size and buried depth is established, so that the detection results have an interpretable physical basis. The breakthrough of system

integration is reflected in the non-contact and synchronous control of UAV flight platform, high-pressure jet device and voiceprint acquisition system. With the help of the design of elastic damping bracket and array noise reference channel, the interference of UAV flight noise and airflow disturbance on voiceprint signals is effectively suppressed, so that high-quality voiceprint data can still be obtained under the conditions of 10 meters flight altitude and 0.4 MPa water pressure, which solves the long-standing problem of signal-to-noise ratio in this field. In the aspect of algorithm design, a heterogeneous feature vector is proposed, which combines the peak factor in time domain, the peak frequency in frequency domain and the resonance drift in time and frequency domain, and the support vector machine with radial basis kernel is used for pattern recognition. With the help of ten-fold cross validation to optimize the hyperplane decision boundary, the accuracy of 91.2% for the hollowing defects with diameter  $\geq 100$  mm and depth  $\leq 30$  mm is realized, and the sensitivity and specificity are better than those of the single feature criterion, which provides an automatic and non-contact new path for the quality inspection of the external insulation layer of the external wall.

Although the above methods verify the effectiveness of hollowing identification under typical working conditions, there are still some limitations in the current research. On the one hand, the test is only carried out for EPS and XPS board, and the applicability of other common materials in the external wall system, such as rock wool board and polyurethane board, has not been verified. The difference of density and elastic modulus of different materials may lead to the offset of voiceprint characteristics and affect the accuracy of mapping model. On the other hand, the control range of environmental variables is limited. In the test, the wind speed is limited to level 3 and the background noise is less than 55dB. However, in the actual project, the wind speed in the high-rise building area is often up to level 4-5, and the urban environmental noise may exceed 60dB. The quality of voiceprint acquisition and the robustness of recognition under high noise and strong wind conditions need to be further tested<sup>[20]</sup>. In addition, the identification accuracy of the boundary condition of the hollowing size is only 68.3%, which indicates that there is a bottleneck in the perception ability of the method for small hollowing or deep defects, which may be due to the coupling characteristics of the flow excitation energy distribution and the hollowing vibration, which limits the signal intensity. At the same time, the current feature extraction and SVM classifier rely on fixed parameters and lack of adaptive adjustment mechanism for dynamic conditions, such as the peak frequency drift can not be automatically compensated when the injection parameters change.

## Fundings

Scientific Research Project of the Department of Housing and Urban-Rural Development of Zhejiang Province in 2025, "Recognition of Hollowing in External Insulation Layer of External Wall Based on Voiceprint Response of UAV Water Jet" (Project No.: 2025K105). It is also an outcome of Construction Engineering Innovation Center of Department of Housing and Rural-Urban Development of Zhejiang Province-Smart Testing.

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## References

- [1] Yang Shun. Intelligent recognition and grading warning of building exterior wall insulation layer defects based on UAV thermal infrared images [J]. UAV, 2026, (8): 172-174.
- [2] Tan Xiang, Ji Yingbo. Study on damage location and quantitative assessment method of building exterior insulation system [J]. Special Structures, 2026, 43 (3): 116-122.

[3] Zhao Shuo. Research on Residential Envelope Detection and Green Transformation Based on UAV Aerial Survey: Taking Jinan Area as an Example [D]. Tutor: Cui Yanqiu. Shandong Jianzhu University, 2025.

[4] Zhang Dongjie. Research on Testing Method of Thermal Insulation Performance of External Wall of Heating Residential Building Based on UAV Infrared Thermal Imaging [D]. Tutor: Zhan Changhong. Harbin Institute of Technology, 2024.

[5] Zhang Fan, Liu Tianyu, Zhang Haige, Sun Wenbo. Application of UAV Infrared Thermal Imaging Technology in Quality Inspection of Building Exterior Wall Insulation Layer [A]. Engineering Construction Committee of Architectural Society of China, China Construction Eighth Engineering Bureau Co., Ltd., China Construction Science and Technology Group Co., Ltd., Asia-Pacific Construction Science and Technology Information Research Institute Co., Ltd., National Building Green Low Carbon Technology Innovation Center, Shandong Construction Industry Association, Shandong Intelligent Construction Industry Development Alliance, Civil Engineering Construction Industry Science and Technology Forum (2024) and Proceedings of the 15th China Construction Eighth Engineering Bureau Science and Technology Forum [C]. China Construction Eighth Engineering Bureau Co., Ltd.; China Construction Eighth Engineering Bureau Fourth Construction Co., Ltd.; Construction Technology Editorial Department, 2024: 161-164.

[6] Ni Yin. Research on Application of UAV Thermal Imaging Detection Technology in External Wall Repair of Urban Renewal Buildings [A]. Kunming University of Science and Technology, China Construction Science and Technology Group Co., Ltd., Yunnan Civil Architecture Society, Building Structure Magazine, Proceedings of the Symposium on Seismic Engineering Structures in 2024 (Volume 1) [C]. Shanghai Pudong New Area Construction (Group) Co., Ltd.; Editorial Department of Building Structures, 2024: 433-438.

[7] Zang Keyu, Tang Min, Xu Zihan. Unmanned equipment for defect detection of external wall thin plastering insulation system [J]. Construction Science and Technology, 2024, (7): 77-80.

[8] Zeng Qingyu, Zhu Yongli. Discussion on the application of UAV in the quality inspection and monitoring of building envelope system [J]. Green Construction and Intelligent Building, 2023, (6): 78-81.

[9] He Jiabin. Defect Detection and Risk Assessment of High-rise Building Tiles Based on Infrared Thermal Imaging Rapid Recognition Technology [D]. Tutor: Xu Hu. Southwest Jiaotong University, 2023.

[10] Ji Lei, Cao Xiaochao, Ni Jiayu, Shi Chun, Peng Cheng, Sha Shaotong, Zhao Guangzhi, Xu Guodong, Gong Hui. Application of UAV in safety appraisal of external wall insulation system [J]. HVAC, 2022, 52 (S1): 466-467.

[11] Li Silin. Research on Intelligent Inspection Planning Method of Urban High-rise Building Exterior Wall by UAV Based on BIM [D]. Tutor: Tan Yi. Shenzhen University, 2022.

[12] Li Geng. Research on Building Exterior Wall Disease Location and Visualization Method Based on BIM and UAV Vision [D]. Tutor: Tan Yi; Li Zeyu. Shenzhen University, 2022.

[13] Chen Wenhong. Research on defect detection system of building exterior wall insulation layer based on quadrotor UAV [D]. Tutor: Duan Zhongxing. Xi'an University of Architecture and Technology, 2022.

[14] Zheng Haichao. Research on heat loss evaluation method of heating building envelope based on UAV infrared thermal imaging technology [D]. Tutor: Zhao Lihua. South China University of Technology, 2022.

[15] Jiao Chenlin. Research on Defect Detection and Recognition of External Insulation Layer of Building Exterior Wall Based on Infrared Image [D]. Tutor: Duan Zhongxing. Xi'an University of Architecture and Technology, 2022.

[16] Wang Pujin, Xiao Jianzhuang, Duan Zhenhua, Li Chunlai. Development Trend of Intelligent Damage Detection for Building Facades [J]. Journal of Architectural Science and Engineering, 2022, 39 (4): 24-37.

[17] Chen Ning, Wang Juan, Dong Qingguang. Influencing Factors and Case Analysis of Defect Detection of External Wall Insulation System by UAV with Infrared Thermal Imager [J]. Construction Technology, 2020, 49 (9): 12-15 + 23.

[18] Liang Yixun. Research on Defect Identification and Evaluation Method of External Thermal Insulation

System Based on Infrared Thermal Image [D]. Tutor: Wang Zheng. Harbin Institute of Technology, 2021.

[19] A X P , A L C , A K S ,et al.A lightweight low-cost and multipollutant sensor package for aerial observations of air pollutants in atmospheric boundary layer[J].Science of The Total Environment, 2020.DOI:10.1016/j.scitotenv.2020.142828.

[20] Mutis I , Romero A F .Thermal Performance Assessment of Curtain Walls of Fully Operational Buildings Using Infrared Thermography and Unmanned Aerial Vehicles[J]. 2019.DOI:10.1007/978-3-030-00220-6\_84.