Robot Assisted Wall Inspection for Improved Maintenance of High-Rise Buildings

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ABSTRACT: A robotic system is designed for the express purpose of facilitating timely maintenance of the external walls of high-rise buildings, including inspection and cleaning. This paper addresses the application of a selected method of non-destructive inspection (NDI) to assess the quality of bonding of the tile-wall in such buildings. The basis for checking with the proposed method whether there are voids in the bonding and for evaluating the approximate size and spread of voids is established. The results obtained experimentally with the use of prepared specimens and on physical walls in a university campus are presented and discussed, confirming the validity of the method proposed.

KEYWORD: High-rise buildings, Nondestructive inspection, Robotic maintenance

1. INTRODUCTION

With more and more popular use of tiles on the external walls of high-rise buildings, bonding quality degradation of tile-walls, caused by improper installation or aging, would cause potential environmental damage or fatal danger to pedestrians. For instance, a piece of tile weighing 250g may gain a momentum of 60Nm when falling from the 10th storey of a building[1]. Therefore, safety measures introduced for regular maintenance of tile-walls of tall buildings is of paramount concern.

However, characterized as troublesome, expensive and not too safe, the traditional approach of installing scaffoldings or deploying manned gondolas to carry out periodic manual checking and inspection is susceptible to human fatigue and inconsistency. Thus there is an urgent need for an automatic nondestructive tile-wall inspection method by which the signals obtained can be both recorded and analyzed in an objective way to improve the inspection quality. Meanwhile, with rapid advances in robotics and automation techniques, applying them to enhance the human safety and working condition of maintenance operators and facilitate fast inspection of large areas with program control is worth serious consideration.

Nondestructive methods for assessing and testing the integrity of bonded structure have been widely investigated. A large number of non-destructive inspection (NDI) cases on floors, bridges, beams, or pavements using ultrasonic detection and vibration parameter analysis have proved their practical utility[2][3][4][5]. However, considering the robotic tile-wall inspection of high-rise buildings, a common limitation of these two methodologies is that good contact between the sensor (ultrasonic transducer, vibration element, or accelerometer) and specimen must be kept with the use of a bonding liquid or a high pressure to guarantee their effective coupling, which is difficult or inconvenient to be realized at heights or on large tested areas. Avoiding the need to glue the sensor with the tested structure, the method using impact sounds[6][7][8] is selected and investigated for non-destructive monitoring of bonding quality.

A novel high-safety tile-wall inspection robotic system to service the maintenance of wall tiles is introduced in this paper. To establish the practical means of void identification and void size and spread evaluation on tile-walls of high-rise buildings, the theoretical basis and impact-sound interpretation of the NDI method are first presented. Then some experimental results on specimens and site tests are provided to verify the proposed method. Finally, some discussions on the findings and conclusions are included. The project is code-named NATURAL (*n*on-destructive *a*ssessment of *t*ile-walls *u*sing *r*obot *a*ssisted *l*ocalization).

2. BASIS OF IMPACT-SOUND DETECTION OF VOID EXISTENCE

Understanding the dynamics and resulting sound radiation by impact on solid and void-filled tile-walls is essential for the successful development of impact-sound detection techniques. One approach for analyzing the impact dynamics is to use the spring-mass model [9][10].

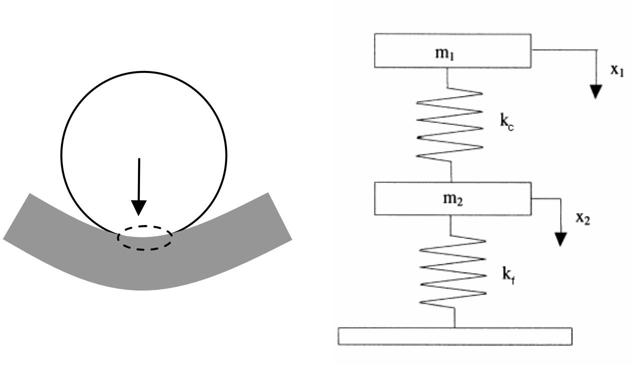

Figure 1. Spring-mass model of impact

For simplicity, a two-degree-of-freedom spring-mass model (see figure 1) is employed, consisting of one spring with K_f representing the bending stiffness of the tile-wall, another spring with K_c representing the nonlinear contact stiffness, and two bodies with M_2 and M_1 representing the effective mass of the tile-wall structure and of the impacting sphere respectively. In the impact of the two masses, the equations of dynamics of the system can be written as:

$$M_1 \frac{dx_1^2}{d^2t} + P = 0 \tag{1}$$

$$M_2 \frac{dx_2^2}{d^2t} + K_f x_2 - P = 0 \tag{2}$$

$$P = K_c \cdot \alpha^{3/2} \tag{3}$$

$$\alpha = x_1 - x_2 \tag{4}$$

where P is the contact force which is a nonlinear function of the indentation α .

Considering the energy distribution in the system, the original kinetic energy of the sphere is used to deform the structure during impact. Assuming that the structure behaves quasi-statically, when the structure reaches its maximum deformation, the velocity of the sphere becomes zero and all of the initial kinetic energy will be converted to the energy stored by the deformation of the structure. Therefore, ignoring the shear and membrane components of structure deformation, the energy balance equation can be given as

$$E_{sum} = \frac{1}{2} M_1 v_0^{\,2} \approx E_f + E_c = E_f + E_{c1} + E_{c2} \tag{5}$$

where v_0 is the initial velocity of the sphere, the subscripts f, c refer to the energy stored in the structure's bending deformation and contact region's indentation (c_1 for sphere, and c_2 for plate) respectively. Defining *vibration energy loss factor* λ as the ratio of energy transformed to flexural vibration of the plate structure during the impact, according to [11], the following expression can be obtained

$$\lambda = \frac{E_f}{E_{sum}} = \frac{1}{16} \cdot \left(\frac{M_2 K_c}{\rho h K_f} \right)^{1/2} \tag{6}$$

where h, ρ are the thickness and density of the plate respectively, and

$$K_c = \frac{4}{3} E \cdot R^{1/2} \tag{7}$$

$$K_f = \frac{4\pi h^3}{3a^2} \cdot \left(\frac{E_2}{1 - v_2^2} \right) \tag{8}$$

where parameters R and E are defined as $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}; \frac{1}{E} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2}$, where R_1 and R_2 are the radii of curvature of the two impacting bodies (for the case of the impact between sphere and plate, $\frac{1}{R_2} \approx 0$), and a is the radius of the plate. The Young's modulus and Poisson's ratios of the two bodies are E_1, v_1 and E_2, v_2, respectively.

To simplify the analysis, λ can be given as:

$$\lambda = \frac{a}{h^2} \cdot Q_\lambda \tag{9}$$

where Q_λ is a constant representing the properties of impacting bodies. From equation (9), it appears that the ratio of energy converted into flexural vibration is dependent on the thickness and radius of the plate. In the tile-wall structure, the thin tile layer caused by serious bonding degradation has small thickness and effective stiffness leading to much stronger flexural vibration under impact, compared to a solid tile-wall. Based on acoustics theory, the intensity of sound radiation is proportional to the vibration energy. Thus the intensity of sound excited by flexural vibration after the impact can be used as an indicator for the structure-integrity identification of the tile-wall. For simplicity, the sound intensity due to the plate can be written with the use of a constant $Q_{I\text{-}plate}$ as

$$I_{plate} = Q_{I-plate} \cdot E_f = Q_{I-plate} \cdot \lambda \cdot E_{sum} \qquad (10)$$

For energy converted to the deformation of impacting bodies, [11] shows that: the internal deformation energy distribution between two colliding bodies is in inverse proportion to the ratio of their elastic modulus. In other words,

$$\begin{cases} \dfrac{E_{c1}}{E_{c2}} = \dfrac{\alpha_{sphere}}{\alpha_{plate}} = \dfrac{E_2 / 1-v_2^2}{E_1 / 1-v_1^2} & (11) \\ E_c = E_{c1} + E_{c2} & (12) \end{cases}$$

Hence, in the total indentation $\alpha\ (\alpha = \alpha_{sphere} + \alpha_{plate})$ of the contacting region, the part due to the sphere's impact indentation α_{sphere} is fixed and only determined by the materials of the impacting bodies. Then the intensity of resonant sound radiated by the sphere's free vibration excited by impact indentation can be written as

$$I_{sphere} = Q_{I-sphere} \cdot E_{c1} = Q_{I-sphere} \cdot (1-\lambda) \cdot E_{sum} \qquad (13)$$

where $Q_{I\text{-}sphere}$ is a constant. According to the theoretical analysis above, for a degraded tile-wall, the thin tile layer formed by a void separation will lead to the absorption of most of the kinetic energy of the sphere by the plate in flexural mode vibration. For a solid tile-wall, however, the loss of kinetic energy of the sphere is very small. In the meantime, the strength of free vibration of the sphere caused by impact indentation is also affected by the *vibration energy factor* λ.

As a result, the relative intensities of sound radiation excited by the free vibration of sphere and plate can reflect the integrity of tile structure.

Defining R_{ps} as the ratio of sound intensities due to the sphere and plate, we obtain

$$R_{ps} = \frac{I_{plate}}{I_{sphere}} = Q_{const} \cdot \left(\frac{1}{1-\lambda} - 1 \right) \qquad (14)$$

where Q_{const} is a constant representing the properties of plate and sphere material. Because the solid tile-wall generally has a thickness more than 20 times higher than that of the thin layer of detached tile caused by bonding degradation, the ratio of sound intensities due to the sphere and plate after impact R_{ps} will appear significantly different in the presence of poor bonding. Using this impact sound method, the need to use coupling agents or apply a high pressure on tile-walls can be avoided.

3. BASIS OF DETECTION OF SIZE AND SPREAD OF VOIDS

3.1 Relationship between void size and fundamental frequency

For the sake of convenience, a void-filled tile wall is modeled as a thin rectangular plate with simply supported edges. Accord to vibration principles, the flexural vibration frequency of different modes can be written as[12]

$$f_{mn} = 0.453 c_L h \left[\left(\frac{m+1}{L_x} \right)^2 + \left(\frac{n+1}{L_y} \right)^2 \right] \qquad (15)$$

where m and n are integers (beginning with zero). From equation (15), the analytical expression for the fundamental frequency of flexural vibration of a thin plate is

$$f_{0,0} = 0.453 c_L h \left[\left(\frac{1}{L_x} \right)^2 + \left(\frac{1}{L_y} \right)^2 \right] \qquad (16)$$

Conclusion can be drawn that the fundamental frequency of flexural resonance will increase with diminishing void dimension if the thickness is the same. In addition, the shape of the void also has a significant influence on the fundamental frequency.

3.2 Void spread analysis

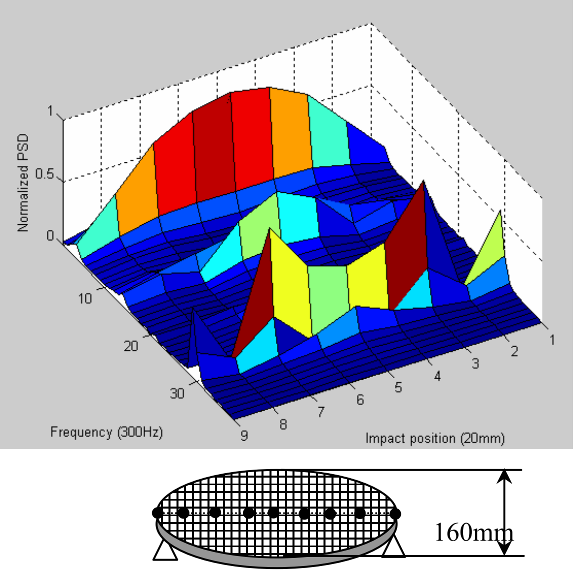

Figure 2. FE analysis of impact positions

Due to the difficulties in theoretical analysis of the relationship between sound radiation and impact position of void, finite element (FE) analyses (see figure 2) are performed to investigate the evaluation of void spread. With the commercial package ANSYS 56, a harmonic analysis of a thin circular plate (with a diameter of 160mm, thickness of 7mm) impacted at different positions above a circular void is conducted. The assumed parameters of concrete are input in the FE model in order to simulate the tile-wall case. Results from FE numerical studies are presented as figure 2 in terms of the normalized spectra for 9 different impacts at points along a plate diameter. It is shown that the relative intensity of the fundamental component will become stronger with the impact location getting nearer to the center of the void.

4. BASIC ROBOT STRUCTURE AND NDT SET-UP

4.1 Basic robot structure

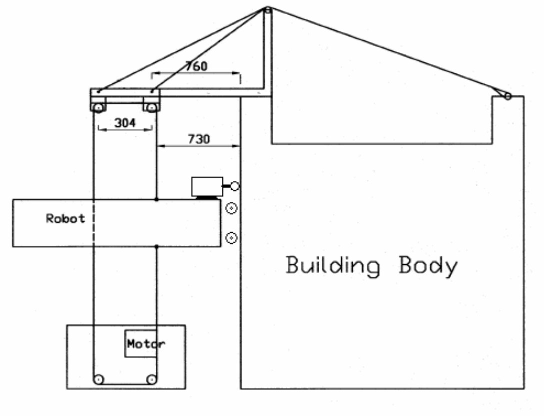

Figure 3. Basic structure of robot

The tile-wall inspection robotic system consists of three parts (see figure 3): robot module equipped with a nondestructive-testing (NDT) device for inspection, ground platform providing cable drive and counter-weight and supporting structure at the building roof. By design, the robotic system facilitates scanning of the entire wall by the NDT tool on high-rise buildings and is easy to install.

4.2 Set-up for NDT experiments

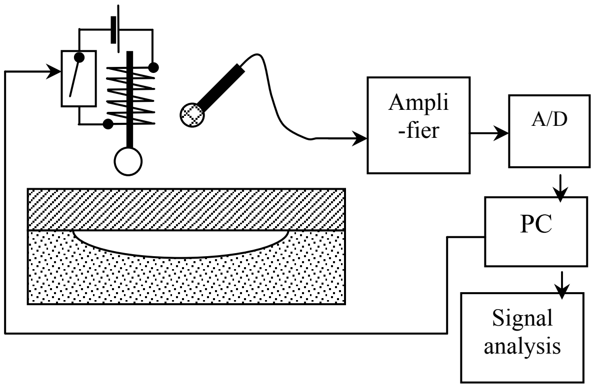

Figure 4. Schematic of NDT experiment set-up

The NDT experimental system is illustrated in figure 4. The apparatus adopted includes: a steel sphere of diameter 23mm triggered by a coil; pre-amplifier module; AD card; microphone. The main advantage of this method is that the impacting device and microphone need not be coupled through the surface of the wall. This is of great convenience for the robot system working at heights. Moreover, it will take less time and effort to perform inspection on large-area tile-walls. For better comparison, concrete specimens and physical tile-walls in the university campus with different voids and tile types are used as test cases.

5. EXPERIMENTAL RESULTS BASED ON SPECIMEN AND SITE TESTING

5.1 Impact sounds and bonding degradation

From the analysis above, the ratio of sound intensities due to the plate and sphere after impact defined as R_{ps} may be used as an indicator to identify the bonding degradation of tile-walls in the NATURAL project. Because of the mixing of sounds from plate and sphere in time domain, R_{ps} is calculated in frequency domain by measuring the areas under the power-spectral-density (PSD) curve of corresponding bands. Shown in figure 5 is the site-test result on a physical tile-wall which can be consistently explained with the previous analysis. Values of R_{ps} on void positions are much larger than those on solid positions.

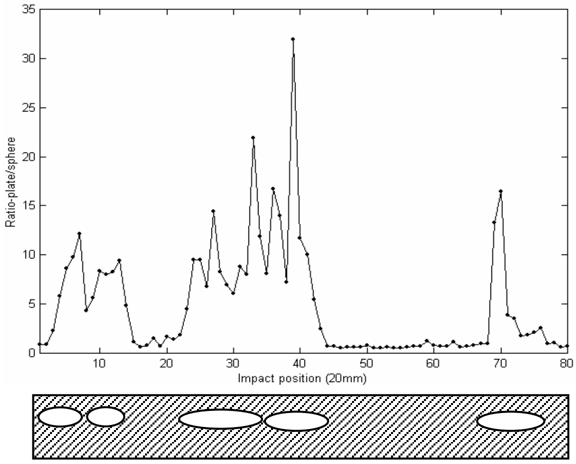

Figure 5. Sound intensity ratio R_{ps} of corresponding voids

Fluctuations of ratio values in figure 5 are caused by various factors such as the directivity[13] (ignored in previous analysis) of sound-radiation fields, different impacting positions, saturation effects of microphone and background noise. Meanwhile, it should be noted that the variation of R_{ps} is a continuous curve when the impact takes place from solid to void positions. Therefore, suitable judgement should be made to ensure realistic recognition.

5.2. Impact sounds and void size

The analysis in 3.1 provides the theoretical feasibility to estimate the void size of the thin plate (with a void underneath) on the basis of the fundamental frequency of flexural vibration. The differences between solid and degraded (with various void sizes) tile-wall surfaces are verified by impact sounds obtained from specimens and tile-wall site tests (see figure.6-10 for representative results.)

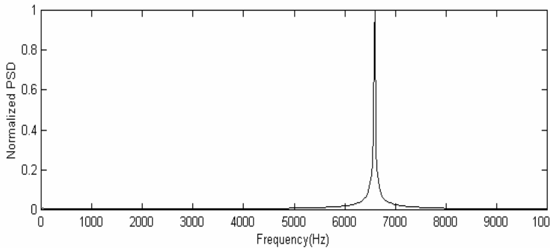

Figure 6. Spectrum of impact sound from solid tile wall

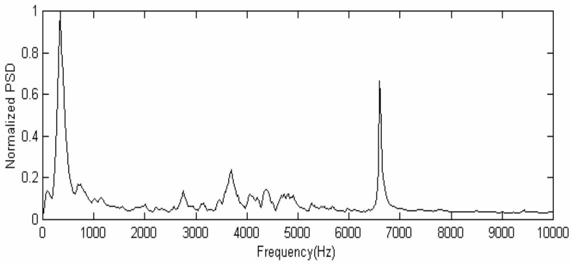

Figure 7. Spectrum of impact sound from concrete specimen (void size: 240mm×190mm)

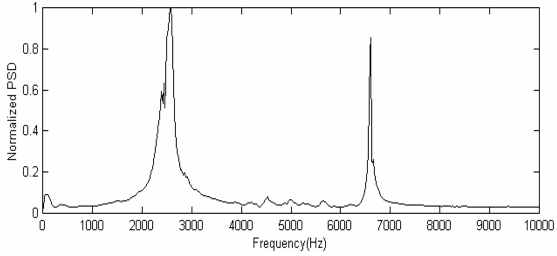

Figure 8. Spectrum of impact sound from debonded tile wall (void size: 160mm×114mm)

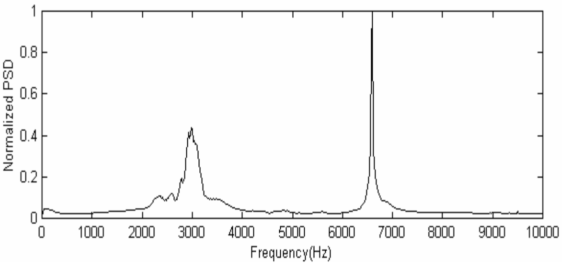

Figure 9. Spectrum of impact sound from debonded tile wall (void size: 120mm×114mm)

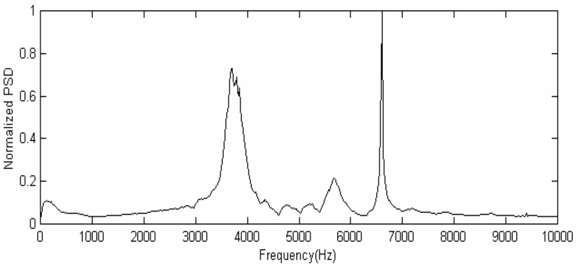

Figure 10. Spectrum of impact sound from debonded tile wall (void size: 80mm×114mm)

In the figures, a stable spectral peak at about 6.7 kHz is created by the free vibration of the steel sphere. The resonance frequency components below this peak come from flexural mode vibration of void-filled tile structure. As seen from figure 7 to figure 10, with decreasing void dimension, the measured fundamental frequency increases from about 300Hz to 2.3kHz, 2.9kHz and 4.0kHz.

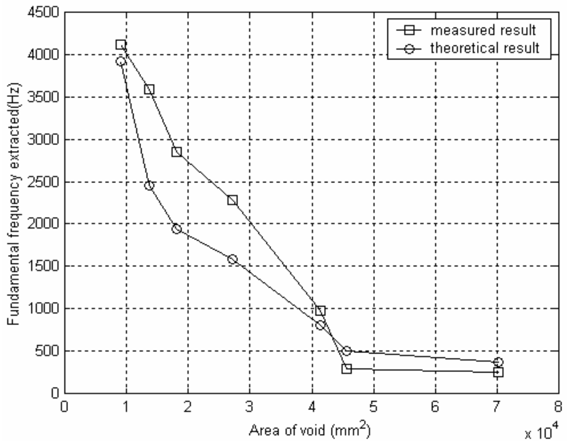

Figure 11. Theoretical and measured fundamental frequency for cases with different void sizes

For comparison, the measured and theoretical (with assumed parameters) fundamental frequencies for 7 cases with different void sizes in the specimens and site tests are plotted in figure 11. The experimental results obtained confirm the general validity of the theoretical analysis above. Because the aim of void-size evaluation is just to provide a coarse reference for the maintenance planner or operator, high precision is not required.

5.3 Impact sounds and void spread

With the help of a specially designed specimen, sounds excited by impacts at positions located from one side to another of a rectangular void (void size: 240mm×190mm) are recorded and analyzed. As shown in figure 12, the fundamental flexural vibration component becomes apparently stronger when the impacting position moves close to the void centre. Impacts near the edge of the void create sounds with weak fundamental frequency. This agrees well with the trend obtained by FE analysis in 3.2 and the information is useful for void spread evaluation.

See figure 12

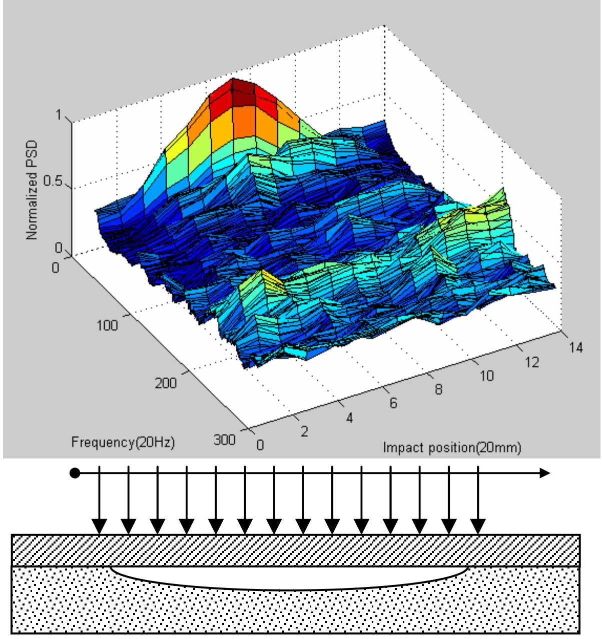

Figure 12. The relationship between natural frequencies and corresponding impact positions

6. CONCLUSION

To be used for high-rise building's robotic tile-wall health monitoring, an NDT method employing impact sounds is developed in the NATURAL project. The model of impact-sound radiation is set up to offer a basis for the signal interpretation. It leads to the conclusion that: the bonding quality of tile-walls will be reflected by the relative intensities of different resonance components, and the fundamental frequency of flexural resonance provides an acceptable indicator to estimate the size and spread of voids. Different specimen and site tests presented show general agreement with the theoretical analysis. The effectiveness of the proposed NDI method is hence demonstrated. Future work will be focused on the performance improvement of void inspection and feature evaluation through further investigation on directivity of sound-radiation field and impact positions.

7. ACKNOWLEDGEMENT

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