# A Haptic-Inspired Approach of Ultrasonic Nondestructive Damage Classification

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***Abstract*—This paper adopts the idea of involving human subjects in making structural damage detection and classification decisions. Inspired by human haptics, ultrasonic guided wave scattering information is transformed into audible signals rather than tactile excitations. Ultrasonic waveforms are encoded melodically or chordally into audio signals. Human subjects are trained on these encodings and subject to blind tests. Damage conditions, manifested as scattering changes, are enabled through the scattering matrix to and also audio-encoded for comparison to melodic and chordal encodings. The performance is better than the cases encoded with raw data, as there is more straightforward physics contained in the feature domain.**

***Keywords—Structural Health Monitoring; Nondestructive Evaluation; Haptics; Ultrasound; Audio Encoding; Scatter Matrix***

## I. Introduction

There are five basic senses that humans adopt to interact with the world, namely, vision, aural, tactile, taste, and smell. Compared to computational algorithms, human decision-making is often more adaptive and robust, which leads to a better potential in interpreting engineering data and handling ambiguities [1]. Haptics has been applied to the structural health monitoring (SHM) recently, taking advantage of the human capability in processing complex information. A recent study demonstrated how nonlinear impacts due to structural damages were identified via vibro-transducer array embedded in a smart glove, which transforms SHM features to modulated tactile pulses [2]. By means of pattern recognition empowered by human subjects, different tactile stimuli are identified, indicating different damage types and locations to be classified in the SHM. Human has long history of using audio information to interact with surroundings. For example, people determine the moving direction of sound source, as well as recognize the voice from different speakers. Motivated by the successful thrust on applying tactile haptic decision-making, an audio haptic approach is investigated to detect and classify damage, and the feasibility of extending haptics-enhanced SHM to the sense of hearing [3]. Instead of encoding audio tracks based on the raw SHM data, this paper will focus more on the scattering features and generate sound series that reflect the scattering matrices under different damage scenarios.

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## II. Audio Encoding via Raw Series

Based on ultrasonic guided wave nondestructive evaluation technologies, Fig. 1 shows how the raw data are processed in [3]. As a tone burst of excitation is applied to the structure, the wave gets propagated through the media, and mechanical responses at different locations are recorded. Subtracting the response by corresponding signal at an undamaged baseline condition, a residual signal is obtained, which contains the time-of-flight information and may be utilized to detect and locate damage.

In [3], there are two approaches presented to encode the baseline-subtracted residual, namely chordal and melodic approach. Fig. 2 demonstrates the chordal method for encoding. Here, a section of time series is selected, and the envelope peaks are extracted to serve as the weight of certain pitches. The outcome of this algorithm is a tonal group ("chord") played with the volumes corresponding to the magnitude of each peak.

Fig. 1. Flow of audio-haptic encoding via raw series

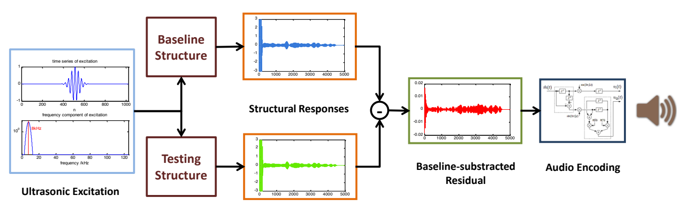



Fig. 2. Chordal encoding of raw SHM series

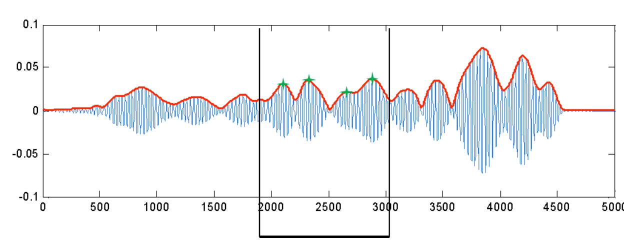
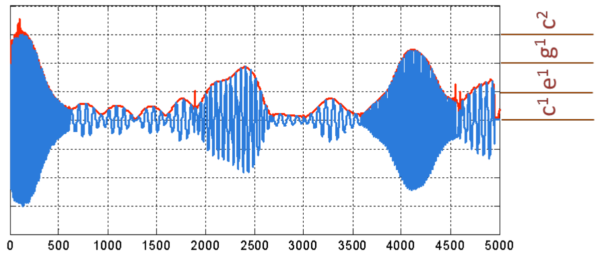


Fig. 3. Melody encoding of raw SHM series




The other encoding algorithm concerns the distinction of encoded sound tracks from different damage conditions. In the previous chordal approach, all pitches/tones are played at the same time, and there is no change with respect to time. For common test subjects without professional music training, it is difficult to differentiate the inconsistency between conditions, especially memorize the inconsistencies for group classification later on. Fig. 3 demonstrates the idea of melody encoding, in which the magnitude of each wave pack is mapped to pitch as well as volume, i.e. the higher the wave pack is, the higher the encoded frequency is, and the louder the audio signal is at the same time.

The haptic damage detection and classificaiton is implemented among human test subjects, as shown in Fig. 4. A detailed discussion is available in [3], and in this paper, a more SHM-feature-based approach will be adopted and compared to the results in Fig. 4.

Fig. 4. Human subjects testing results via raw SHM data

| | #1 | #2 | #3 | #4 | #5 | #6 |
|---|---|---|---|---|---|---|
| Chord | 3/12 | 2/12 | 5/12 | 4/12 | 3/12 | 4/12 |
| Melody | 7/12 | 6/12 | 6/12 | 7/12 | 10/12 | 12/12 |

## III. Scattering Characteriscs of Damage

When a guided wave is travelling through a medium, discontiouities in the material and/or structure will scatter the wave. If the discontinuity is shaped and oriented in certain directions, the wave field after reflection and scattering will be unique to the damage characteristics, such as the shape and size of a hole or the length and the direction of a crack, and this will be observable as scattered energy in the far-field approximation.

Fig. 5 defines the finite element model of a contrived plate ABAQUS, and ultrasonic wave excitation is applied and measurements are taken at various positions, with the same distance to the center of the circle. Fig. 6 lists six different wave propagation patterns under different damage conditions, namely three different sizes of holes and three differently-oriented cracks. Generally speaking, the scattering and reflection is getting more obvious as the projected defect size along the propagation path increases.

To be more quantitative, the relative attenuation caused by the scattering between any directions, i.e. incident and scattered directions, is characterized by a scattering matrix, and it fully describes the wave propagation under such damaged scenarios, as (1) shows:

$$S(\theta_1,\theta_2)=\frac{u_s}{u_0}\sqrt{\frac{r_2}{\lambda}}c^{-ik(r_2-\lambda)}. \qquad (1)$$

Fig. 5. Wave propagation FEM model

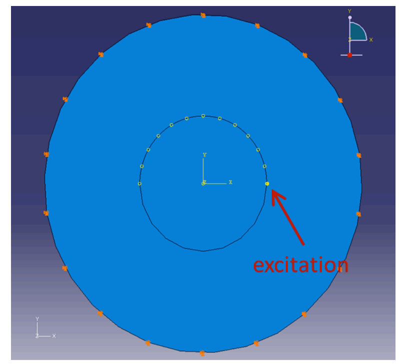



Fig. 6. Wave propagation patterns with different damages

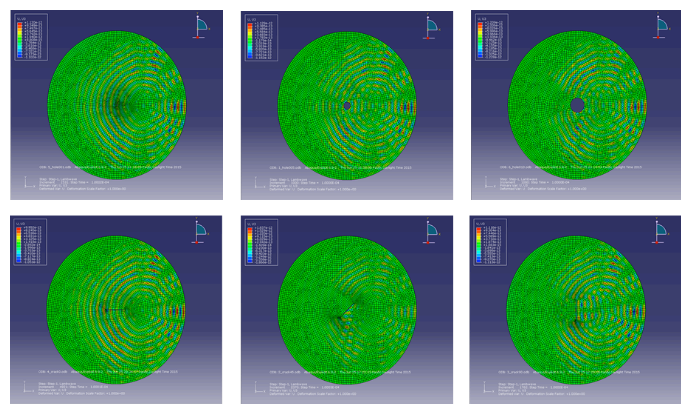
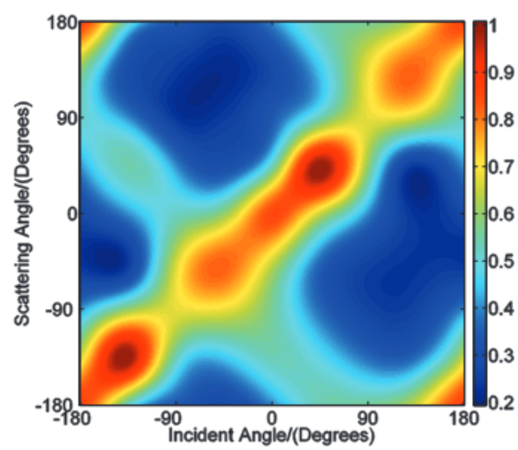


Fig. 7. Example of 2-D scattering matrix [4]



In (1), $\theta_1$ and $\theta_2$ are the angle of the incident and scattered direction, and $u_0$ and $u_s$ are the magnitude of incident and scattered waves. In (1), $\lambda$ is the wavelength of the ultrasonic wave, $k$ is the wavenumber, and $r_2$ is the distance of scattering measurement from the defect. The full picture of $S$ is given by all the combinations between the $\theta_1$-$\theta_2$ pair, and this will form an n-by-n grid and can be plotted as a 2-D map, as shown in Fig. 7, which is from Chen, Michaels and Michaels [4]. The scattering matrix clearly delivers the information that, at certain incident direction, what the attenuated magnitude of scattered wave at all directions will be.

## IV. Audio Encoding via Scattering Features

Encouraged by the melody encoding algorithm in previous section, the scattering map as shown in Fig. 7 is regarded as a spectrogram of the signal to be encoded. In more detail, the horizontal axis will be treated as time, and the vertical axis will be treated as frequency, or pitch in the context of music encoding. Considering the symmetry of the plot, as well as the complexity of encoded sound tracks, only half of the matrix is considered in the construction algorithm, as illustrated in Fig. 8.

As previously addressed in [3], there are only harmonic notes that will make the haptic training sustainable. In other words, if there are too many inharmonic intervals in the sound tracks, the human test subjects will get tired very quickly and the damage identification performance degrades dramatically. Moreover, there is a trade-off between the number of notes and the distinguishability. When there are too few notes, the sound tracks from different testing cases may not be distinguishable, yet if there are too many notes, the problem becomes complex and goes beyond a typical human's capability. Because of the uncertainty induced by operational and environmental variability, extraneous noise is applied onto the scattering matrices to blur the plots, and the audio tracks will thereby be different from test to test even under the same damage scenario.

In this paper, a 7-step discretized pitch scale is considered and only C, E and Gs are included in the encoding to gaurantee harmonic melodies. In Fig. 9, the multiple scattering matrices from Flynn [5] are cited to deploy the encoding algorighm. As Fig. 9 shows, there are six damage conditions in total, representing respectively a 5-, 20-, and 80-mm crack and a 2.5-, 5-, and 7.5-mm-diameter hole. As mentioned above, only half of the matrix will be considered to simply the problem due to symmetry.

Fig. 8. Melody encoding of the scattering matrix

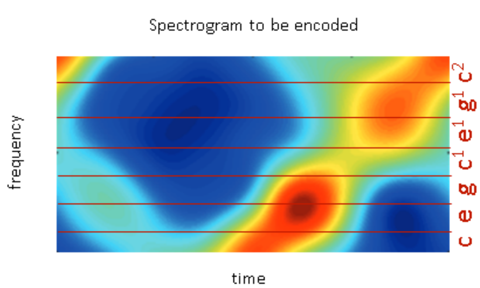
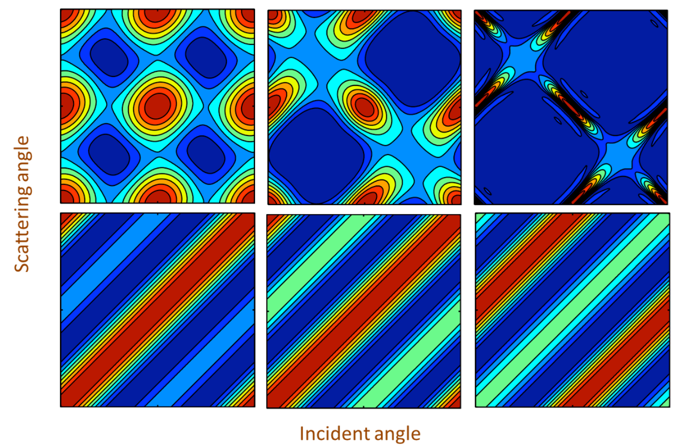



Fig. 9. Scattering matrices of different damage cases. Upper row from left to right: 5-, 20-, and 80-mm crack; lower row from left to right: 2.5-, 5-, and 7.5-mm-diameter hole [5]




Implementing the audio encoding algorithm introduced earlier in this paper, a bundle of audio signals is generated corresponding to the aforementioned six damage conditions.

Fig. 10. Spectrogram of the encoded melodies for different damage conditions

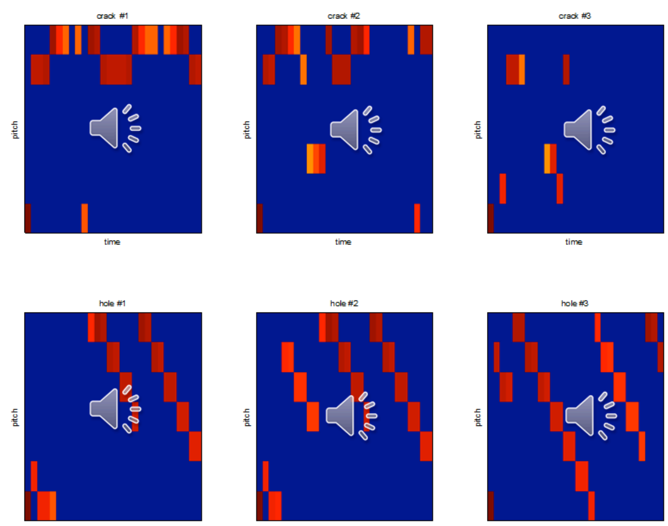



Fig. 10 illustrates the spectrogram of all six encoded audio sound tracks, corresponding to the aforementioned six damage conditions and these tracks, as well as the testing cases with unknown damage conditions are played to the human subjects. The set-up of audio testing will be discussed in more detail in the next section.

## V. Audio Damage Identification via Scattering Features

In this work, there are 6 damage conditions included in total, and the training is deployed to all human subjects for about fifteen minutes. Besides the 6 training cases, there are another 18 testing cases that include 3 cases from each damage condition. The testing cases are contaminated so that they are not exactly the same as what the human subjects heard during the training, neither the same as other testing cases within the same damage group.

A testing sheet is designed for human subjects to take notes during the training and facilitate their decision-making later in the tests. Fig. 11 demonstrates how those test subjects take notes in their own ways. The straightforward way that most subjects adopt is to draw down the music as a curve, and follow the pitch and pause of the sound track. More sophisticated notes are taken with extra symbols such as circles, dots, and space characters. The most accurate notes are taken by human subjects with instrument training experience, and they are able to write down the scores of the music, which proved very helpful during the testing afterwards. However, no matter what notes the testing subjects take, the damage identification decision is made under a human haptic sense, and notes only remind them about the "feeling" that they had during the training. In short, the human subjects extract the useful features, yet inexplicit and probably unknown by the subjects themselves, to make classification decisions, rather than just reading the notes taken in the training.

Fig. 11. Testing sheet and notes the human subjects take

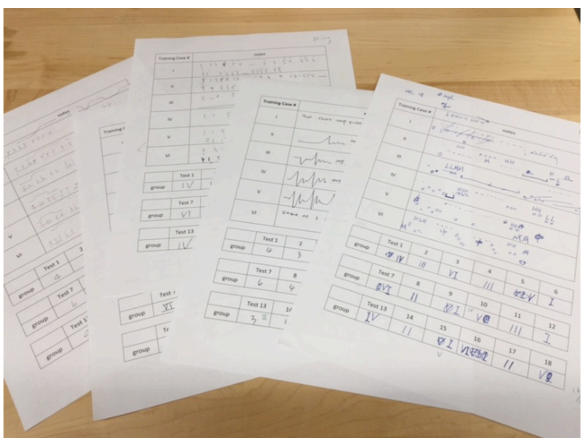


Fig. 12. Testing results of the audio-haptic damage identification

| | #1 | #2 | #3 | #4 | #5 | #6 |
|---|---|---|---|---|---|---|
| score | 18/18 | 18/18 | 16/18 | 18/18 | 14/18 | 8/18 |

In Fig. 12, the scores of all testing subjects are listed, which are the numbers of correct classifications over the entire tests, i.e. 18 in this work. The first two test subjects had musical instruments experience and are regarded as "pre-trained" before the haptic testing is really conducted. So they are better trained in term of sense of music. All the rest are randomly picked with different level of musical gift, but they all classify the damages promisingly. Even the test subject with the lowest success rate categorizes the damages much better than random guess, which is 3/18.

## VI. Conclusion

In this paper, audio-inspired haptic damage detection is investigated via the scattering characteristics of ultrasounds. Compared to the previous research using raw signal from ultrasonic nondestructive evaluation, this new approach leads to a better performance and delivers more decisive information. There are multiple damaged types and dimensions included in the classification problem, and all the human testing subjects are able to classify the damages significantly better than a random guess. Among all the human subjects, half of them get 100% correct, and the results suggest a promising potential to embed the audio-inspired haptic decision-making into SHM applications. The manner in which the audio signals were encoded could also easily be converted into tactile (true haptic-based) signals, and this is the subject of future work.

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