Correlation of Accelerometer and Microphone Data in the “Coin Tap Test”

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Abstract

In the “coin tap test”, an operator taps with a coin-like light tool on the structure to be inspected, feeling the subtle difference of impact force and hearing the resulting sound to discriminate defective regions from normal ones. The test remains largely subjective, and there has been considerable uncertainty about the physical principles behind it. Analyzing and comparing the force measured by an accelerometer in the hammer and the resulting sound recorded with a microphone, this paper seeks an understanding of the fundamental principles underlying the individual measurement techniques. It gives a paradigm for sensor fusion via using the data from one modality to select the optimal time window for signal analysis of another modality.

I. INTRODUCTION

The “coin tap test” is a venerable means for manually verifying the integrity of objects and structures, particularly sheet-like and layered materials that are subject to cracking and delamination. An operator taps with a small hammer (or a screwdriver handle or some other light-weight object, like a coin) the structure to be inspected, meanwhile feeling the rebound of the hammer and listening to the resulting sound radiated by the impact. Healthy examples typically reverberate cleanly (they sound “live”), whereas damaged examples yield a sound that is dull (“dead”). The operator can discriminate defective examples from good ones by discerning the differences.

The classical theory of impact, which assumes that the kinetic energy transformed into the body’s vibration is negligible, is incapable of describing the transient forces, stress, or the deformations produced; thus it cannot explain the interaction force profile and the “ring” we hear. The analysis of impact and vibration requires including elasticity and plasticity, which generally does not yield a closed-form solution.

Following the wave motion theory of elastic solids articulated by Goldsmith in the 1950s [4], Cawley numerically simulated a few impact cases between a light hammer and a free-free beam [5]. Figure 1 illustrates a typically calculated interaction force profile (the solid curve) with this method.

The asymmetry in the expected waveform is due to non-linearity associated with non-rigid body behavior. Severe non-linearity comes from the change in the number of modes excited (as shown in Cawley’s analysis), and also from the dependence of energy dispersion and attenuation on the impact force magnitude.

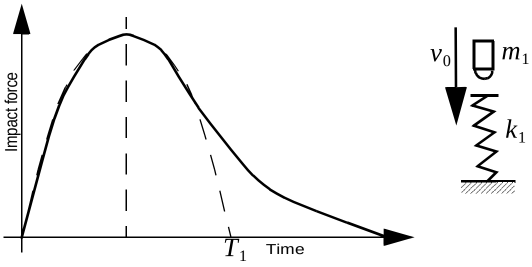

FIGURE 1. Expected force-time curve

All currently reported coin-tap research avoids these mathematically enormous difficulties by approximating the hammer impact process by a half-cycle sinusoidal vibration. The contact time T_1 is then just a half cycle of the mass-spring oscillation:

$$T_1 = \pi \cdot \sqrt{m_1 / k_1} \qquad (\mathrm{E}\Theta\ 1)$$

II. AVAILABLE PRODUCTS AND OUR EXPERIMENTS

A. Commercially Available Products

The Mitsui “Woodpecker” [1] (advocated by Airbus for nondestructive testing of composite laminated aircraft skin components) and the WichiTech “RD3” instrumented hammer [2] (a commercial version of apparatus developed by Georgeson et al at Boeing [3]) are two available products. The Mitsui product uses a solenoid-driven hammer and the WichiTech product uses a hand-wielded hammer; both instruments measure essentially the output of an accelerometer embedded in the hammer head. Basically both instruments base their judgements on just the contact time duration referenced to a normal sample; however in Mitsui’s patent document [6] a method of using the force/acceleration-time history asymmetry measurement was also mentioned. Rolls-Royce’s “MetEval Tapometer” is similar, but it makes some use of the acceleration frequency spectrum in addition to contact time.

An alternative way of implementing the traditional coin-tap test is to analyze the impact-generated sound data instead of the force data. Bruce Pfund of SP Surveys developed the “Smart Hammer System”, which employs a pneumatically driven hammer, a microphone coupled to the hammer impact through the air, and graphical display of the acoustic Fourier spectrum to help the inspector decipher the anvil’s condition [7] in the ship-building industry. Pfund argues that in complex real world environments, with surfaces in arbitrary orientations and states of contamination, the sound per se, propagated through the air, is the best indicator of subsurface condition.

To investigate whether one approach is better than the other in terms of sensitivity and reliability under similar conditions, we did sound data analyses and compared the results with those of force analysis.

B. Experiments

1). Equipment. The apparatus we use includes: an SGI Indy multimedia workstation with dual-channel audio sampling capability; a Tektronics 2232 dual-channel digital sampling oscilloscope; a small hammer with various material and head weights, inside each of which we mount a Kistler 811AD accelerometer; microphones.

2). Test Samples. To initially evaluate the effectiveness of coin-tap methods and to seek possible improvements, we compare the test results on *patched* versus *normal* airplane skin, with different under-skin structure conditions. We identify two typical types of under-skin structure conditions: *supported*, as those points close to some supporting joists, and *unsupported,* as those points relatively far away from any supporting components.

3). Data Collection. We simultaneously record the acceleration and corresponding sound data on typical normal airplane skin and typical patched skin, with under-skin structure supported and unsupported respectively. The sampling rate is 48 kHz. To keep our experiments consistent with Cawley's and the Mitsui work, we retain frequency components only up to 8 kHz in the initial data analysis. A typical complete acceleration event lasts for less than 10 ms. To safely avoid losing useful information, for each tap we collect 512 points (10.67 ms, frequency analysis granularity ~94 Hz). The data file begins with a quiet lead (36 points, or 0.075 ms). The corresponding radiated sound lasts about 150~200 ms. We take 2048 sound amplitude samples (~43 ms, frequency analysis granularity 23.4 Hz) for analysis.

4). Basic Data Analysis Algorithm. We first measure the contact time duration T_1 between the hammer and the skin. To investigate the force and sound spectrum distributions, we then calculate Cawley's [5] 1/3 power accumulation ratio factor $R_{1/3}$, defined as:

$$R_{1/3} = \left(\sum_{i=1}^{M/3} Pxx(f_i)\right) \Big/ \left(\sum_{i=1}^{M} Pxx(f_i)\right) \qquad \text{(EΘ 2)}$$

where the $Pxx(f_i)$ is the spectral component at frequency f_i, and M is the number of retained frequency components.

III. Data Analysis

A. Acceleration Data Analysis

A typical acceleration-time history curve is asymmetric in shape with notable noise, as shown in the upper part of Figure 2. For each of the four cases, we collect about 10 impacts, manually measure contact duration time T_1, do frequency analysis and calculate $R_{1/3}$. The mean and standard deviation σ of T_1 and $R_{1/3}$ are shown inTable 1

TABLE 1. CONTACT DURATION T_1 AND SPECTRAL $R_{1/3}$

			Normal skin	Patched skin
T_1	supported	mean	0.6114 ms	0.3282 ms
		σ	0.0152 ms	0.0253 ms
	unsupported	mean	0.3856 ms	0.3055 ms
		σ	0.0170 ms	0.0314 ms
$R_{1/3}$	supported	mean	0.3615	0.3595
		σ	0.0025	0.0024
	unsupported	mean	0.3653	0.3526
		σ	0.0019	0.0013

In contradiction to the single-spring model, where in the unsupported case *k* should be smaller, and so the contact time should be longer, we observe a shorter contact time in the unsupported case. We speculate that this happens because in the supported case the impact is coupled to high frequency modes of the stiff under-structure.

B. Sound Data Analysis

Using the identical impacts we used in force analysis, $R_{1/3}$ for sound frequency components from 23.4 Hz up to 8 kHz (close to Pfund's practice, 10 kHz as shown in [8]) are calculated. The mean and standard deviation σ are shown in Table 2.

TABLE 2. SOUND POWER SPECTRAL $R_{1/3}$

$R_{1/3}$		Normal skin	Patched skin
supported	mean	0.3664	0.3703
	σ	0.0029	0.0045
unsupported	mean	0.3735	0.3719
	σ	0.0019	0.0015

C. Surface dynamics and sound re-examination

From Table 1 and Table 2 we know that the $R_{1/3}$ distributions of normal skin and patched skin have a large overlap for supported under-skin condition in both force spectrum analysis and sound spectrum analysis, and a very similar situation exists in sound spectrum analysis for the unsupported under-skin condition. This means that the coin-tap test method, either with force measurement only or with sound measurement only, cannot always distinguish different airplane skin conditions for some given under-skin supporting structure conditions, and their discrimination capabilities are very similar.

As the interesting part of the force-time history is much shorter than the sound duration, there may be some additional potentially useful information in sound data. On the other hand, it is difficult to use the sound signal to deduce the impact nature, so the force-time history profile shape is still the best indicator both to the under-structure complexity and to the impact amplitude.

Coin-tap test reliability might be further improved if we could fuse these two modalities. For example, a common problem is that there are multiple interactions between the hammer and the tested surface in a nominally single tap. The force-time history is too sensitive to be a reliable measurement in this case, but the sound data are nevertheless more consistent here. Figure 2 shows this situation.

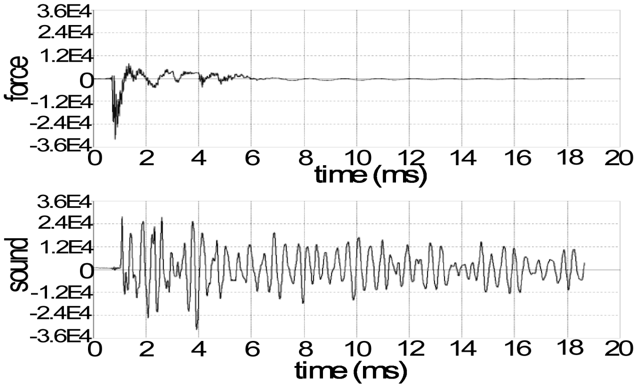

FIGURE 2. Force profile and sound amplitude showing the multiple interaction case.

Clearly, the sound pattern changes after the interaction ends completely. In Figure 3, the power spectra of 6 taps (3 on a typical normal skin point with well-supported infrastructure, 3 on a typical normal skin point far away from any supporting under-skin infrastructures) are overlaid. It is obvious that although the frequency spectra of force (a) and whole-sound waves (b) show definite distribution patterns, the frequency spectrum distribution of the free-vibration sound part (c) is relatively unique.

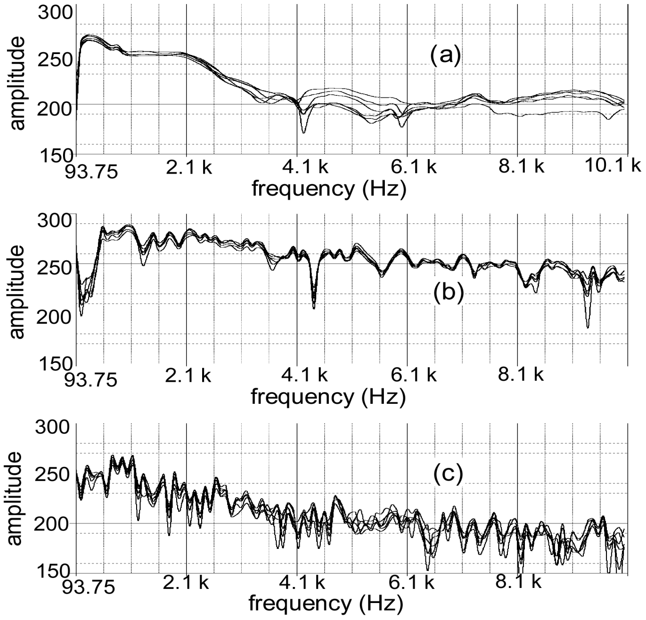

FIGURE 3. Frequency analysis of (a) force-time history (512 samples); (b) whole sound amplitude history; (c) free-vibration part of the sound amplitude history

To further investigate the properties of the free-vibration part of the sound waveform, for the same recorded sound

$R_{1/3}$

TABLE 3. $R_{1/3}$ FROM FREE-VIBRATION

$R_{1/3}$		Normal skin	Patched skin
supported	mean	0.3795	0.3905
	σ	0.0035	0.0045
unsupported	mean	0.3777	0.3892
	σ	0.0027	0.0013

A comparison of Tables 1, 2 and 3 is illustrated in Figure 4, where the heights of bars stand for the mean $R_{1/3}$ value and the lengths of the I-bars stands for the standard deviations σ in that group of ~10 impact measurements. It is clear that for these recorded test data sets, the free-vibration part of the sound data provides the clearest indicator of skin status (normal versus patched condition) independent of the under-skin supporting infrastructures.

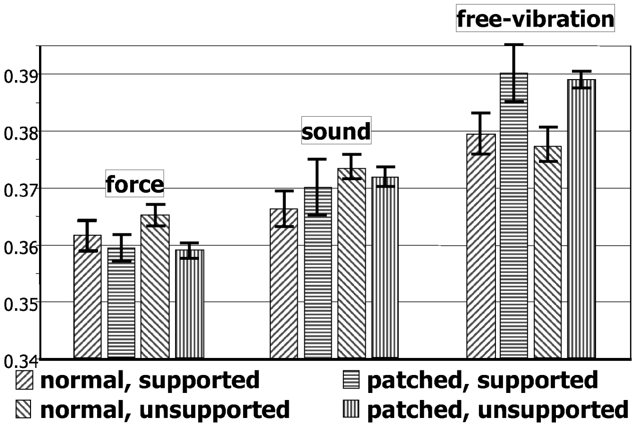

FIGURE 4. The $R_{1/3}$ distribution of force, sound as a whole, and free-vibration part of the sound signal.

This suggests that we adopt a paradigm in which the force-time history data are used to decide whether the particular impact is good one for detecting a particular type of defect, and if it is, then to detect when the interaction between the hammer and surface ends, at which point the free-vibration part begins. This last part of the sound history is the most useful clue for surface shallow defection.

IV. CONCLUSION AND FUTURE RESEARCH

The literature of coin tap test technology, the commercial products now on the market, the instruments being used in key applications (aircraft skins, boat hulls), and our own experimental results, all support our working hypothesis that both microphones and accelerometers have their separate valid roles as instrumentation suitable for automating defect detection. Furthermore, our research results show that by fusion of force and sound sensor measurement — by using one sensor's data to validate the other's — it is possible to make "the whole greater than the sum of the parts". Our experiments lead us toward these conclusions:

- It is hard to say in any universal sense whether force-only or sound-only methods are more useful.
- When the surface being tested is thin, especially when the

under-surface supporting structure is also complex, multiple interactions between the hammer and the surface frequently make the simple single-spring linear model inappropriate.

- The force-time history is a good indicator of whether a particular impact was of appropriate strength, and it serves to locate the start of free-vibration in the sound amplitude record.
- The free-vibration part of the sound amplitude record is more useful than either the whole record of sound amplitude or the force-time history data for detecting surface defects or under-surface structure differences.
- Based on limited data (e.g. Table 3), it seems that we can conclusively discriminate patched vs. unpatched regions, and we may be able to discriminate, within each of these classes, supported vs. un-supported regions. Since the presence of supporting structure is generally known from design drawings, etc., but the location of patches is rarely well documented, the approach seems to be of practical value even at its present early stage.

This paper reports our initial experiments, in which we have investigated patched and unpatched, supported and unsupported samples. We pose these extreme cases as archtypical of the continuum of states of lamination condition and substructure solidity that we will encounter with real-world samples. We are now developing practical methods for performing the tap test on a precise regular grid, and for displaying the results in response-map format. These maps are conducive to both human and computer interpretation and understanding.

Because the impact energy deposited by a coin-tap undergoes dispersion and attenuation via excitation and propagation of multiple frequency modes, the relationship between the impact magnitude and the force-time history or the sound amplitude-time history is quite nonlinear. This makes it difficult or impossible to normalize each force-time or sound amplitude-time history against tap-to-tap variations. To overcome this fundamental difficulty, another future research direction is to examine learning methods that utilize a training set representative of the practical range of sample types, hammer types, and impact delivery strategies.

V. REFERENCES

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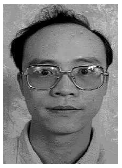
VI. Biography



Huadong Wu received his B.S. and M.S. in Precision Instrumentation, in 1984 and 1987 respectively, from Shanghai Jiaotong University, Shanghai, China. From 1987 to 1995, he worked as an engineer in The Robot & Automation Research Institute in Beijing, China, primarily in robot mechanical design and the control of robot manufacturing systems. He is currently a Ph.D candidate at the Robotics Institute, Carnegie Mellon University, Pittsburgh, PA.

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