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Towards a fracture criterion based on time-scale analysis

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Résumé :

Les tests expérimentaux sont devenus un outil indispensable pour la compréhension du comportement du corps humain en choc et le développement des systèmes de sécurité. Dans le cadre de la sécurité routière, il a été démontré que les lésions du thorax représentent un bon indicateur de la gravité d'un accident. La possibilité de comparer les instants d'apparition des fractures de côtes avec la cinématique des occupants et le déclenchement des systèmes de sécurité permettrait d'améliorer leur conception et la compréhension des mécanismes lésionnels. Il n'existe cependant aucune méthodologie fiable donnant accès à l'état des côtes pendant l'impact : les jauges de déformation actuellement utilisées sont peu précises et couvrir un thorax entier nécessiterait la pose de plus d'une centaines de jauges. Il est proposé dans cette étude une méthode innovante basée sur l'utilisation de transducteurs piézoélectriques (PZT) et l'analyse temps-échelle des signaux. Le sujet d'expérimentation était équipé de PZT sur les côtes 3 et 7 des deux côtés et subit des impacts latéraux au niveau de l'épaule et du thorax. A la suite de chaque impact les fractures furent relevées par palpation et confirmées par une autopsie final. L'étude croisée des analyses temps-échelle des signaux et de la du tableau d'apparition des fractures a permis de définir un critère d'apparition de fracture : un critère d'énergie détecte l'apparition de phénomène transitoire, image de l'apparition d'une fracture. Un seuil énergétique a été défini détectant l'apparition de fracture au cours de l'impact, ouvrant la voie vers la détection des fractures d'un thorax à partir d'un nombre réduit de transducteurs.

Abstract :

Experimental testing is a major source of data to quantify the tolerance of the human body to impact and to develop protection strategies. In the field of vehicle safety, it has been demonstrated that chest injuries are a good predictor of an impact severity. Correlating the time of rib fractures with the kinematics of the occupant and the action of safety systems would provide valuable data for assessing safety systems and developing injury risk functions. However, there is currently no satisfying method to monitor rib fractures: time history analysis of strain gauges data is commonly used for this purpose but this method is not very sensitive and requires to instrument the ribcage with more than 100 strain gauges. A new approach based on time-scale analysis of signals obtained from piezoelectric transducers (PZT) was investigated. A post-mortem human subject was instrumented with four PZT on ribs 3 and 7 on both sides and laterally impacted to the shoulder and the chest. The fractures were documented after each test, and a criterion was developed to process the PZT signals. The criterion consists in detecting in the PZT signal the onset of a high frequency transient generated by the fracture of a rib using the continuous wavelet transform. A threshold was successfully determined to detect fractures that occurred on a rib. Further development of this method should allow the detection of all rib fractures using only a few PZT.

Mots clefs : experimental, signal processing, wavelet transform, thorax, fracture

1 Introduction

A comprehensive understanding of injury mechanisms remains an important and elusive challenge for designers of vehicle safety countermeasures. Tests performed in impact biomechanics allow to reproduce in

the laboratory impact conditions that are observed in real life accidents. In the field of car safety, the chest injuries are a good predictor of an impact severity because rib fractures compromise the ability of the chest to protect internal organs critical to life such as the lungs and the heart. Correlating the time of bone injury with other events such as the kinematics of the occupant and vehicle, the action of safety systems, and measured chest deformation would provide valuable, unbiased data for assessing safety systems and developing statistically based injury risk functions. Moreover, the capability to monitor rib fractures in the case of an impact to the chests would allow to run several non-injurious impact tests on one given subject, either for multiple test conditions or various impact velocities. This would cancel the influence of inter-subject biological variability that alters their mechanical response for a given impact configuration. Performing a CT-scan after each test to assess the rib fractures does not provide the required level of accuracy. Indeed, the only reliable way to document rib injuries is to perform an in-depth necropsy [1][2], because non-displaced fractures cannot be seen on CT images. Non-displaced fractures are however critical to document because they decrease the chest strength [3]. Sensors to identify the timing and location of both displaced and non-displaced bone fractures in the chest during an impact have not been convincingly demonstrated. Strain gauges are commonly used to achieve this goal [4][5][6]. At the time of fracture, strain is released and a brutal drop can be observed in the strain measurement. This drop in the strain time-history is used to determine if and when there was a rib fracture [4]. The limitation in this approach is to rely on the amplitude in the temporal domain: any attenuation in the signal challenges the ability to predict fracture. This limitation is due to the short detection range of the strain gauges. A fracture has to happen within about 50 mm of a strain gauge to be detected by this strain gauge [4]. As a workaround, 5 to 6 gauges per rib are commonly required to properly map the fracture timing of a chest. Installing more than 100 strain gauges per chest is an invasive procedure and requires to set-up the same number of data acquisition channels. An alternative methodology based on time-scale analysis is investigated in the present paper to overcome these limitations. Time-scale analysis (TSA) is a signal processing tool based on wavelet decomposition already used in mechanics to study transient and fast changing signals [7][8][9][10][11] that could be applied to impact biomechanics. Piezoelectric transducers (PZT) are used to measure ribs deformation. PZT transform the mechanical deformation in any direction into a voltage. They are different from strain gauges that measure deformation in only one direction. The goal of this study is to present how TSA can be used to detect rib fractures during an impact test performed on Post-Mortem Human Subjects (PMHS) instrumented with PZT. Six full-scale lateral impact tests were performed on one PMHS. Ribs 3 and 7 on each side were instrumented with a PZT. The rib fractures were assessed after each test. The fracture data were supplemented with the PZT data process. Two fracture thresholds derived from TSA were evaluated to correlate rib fracture occurrence with PZT signals.

2 Materials and methods

2.1 Side impact test

One PMHS (male, 47 kg, 173 cm, cause of death: lung cancer) was selected for this study, based on the absence of pre-existing fractures, lesions or other bone pathology, as confirmed by pre-test computed tomography (CT) analysis. The subject was screened negative for infectious diseases and stored in a freezer (-15°C) until it was removed and thawed at room temperature 48 to 72 hours prior to the pre-test preparation. Incisions were made at the level of the anterior left and right ribs 3 and 7. The soft tissues and periosteum on the section of the rib where the PZT were to be installed were removed to clear the rib bone. The rib bone was then dried with an isopropanol solution to remove grease, the surface of the PZT to be affixed to the bone was covered with cyanoacrylate glue and the PZT was pressed against the bone during about 10 seconds, until the glue hardened. The subject was seated on a simplified seat designed to mimic a standard car seat. The impacts were applied using a pneumatic impactor. A catching system was used to prevent interactions with the ground and avoid any fractures that would be artifact. The impact velocity was 3 m/s. The subject was successively impacted at 3 levels: shoulder (S) with the arm along the chest, upper chest (U) and mid chest (M), both with the arm at 90° flexion. After each test, the ribs fractures were detected via palpation by a physician-researcher with extensive experience in thoracic biomechanics. A careful necropsy was performed after the tests series to document the rib fractures produced by all the 6 tests.

2.2 Signal processing

PZT signals were processed using the Continuous Wavelet Transform (CWT). The continuous wavelet transform of a signal $x(t)$ is defined by equation 1 with $\overline{\Psi}$ indicating the complex conjugate of Ψ , and Ψ is the analyzing wavelet.

$$CWT_x^\Psi(b, a) = \int_{-\infty}^{+\infty} x(t) \frac{1}{\sqrt{a}} \overline{\Psi}\left(\frac{t-b}{a}\right) dt \quad (1)$$

The wavelet transform is fundamentally a correlation between the signal $x(t)$ and a wavelet function $\psi(t)$ translated by b and dilated by a . The chosen mother wavelet function $\psi(t)$, known as the “Morlet” wavelet, is a modulated Gaussian (eq 2). The Morlet wavelet is localized around time $t = 0$ and its Fourier transform is centered on frequency f_0 . It is easily understood that the function $\psi((t-b)/a)$ is localized around $t = b$ and its Fourier transform around $f = f_0/a$. Hence $|CWT(b,a)|$, the magnitude of CWT, represents the square root of the power density of the signal $x(t)$ around the time $t = b$ and the frequency $f = f_0 / a$.

$$\Psi(t) = e^{-\frac{t^2}{2} + j2\pi f_0 t} \quad (2)$$

When a fracture occurs, strains in the material are relieved which generate a high frequency wave in the bone, leading to an increase in the signal frequency bandwidth. Therefore the occurrence of a fracture can be detected by tracking the frequency bandwidth of the PZT signals as a function of time. A criterion was developed to determine the time of fracture by trying to correlate the changes in the frequency width with the fractures documented after each test.

The methodology consists in looking for a wide band of energy at a given time. It is adapted from a methodology proposed by [12]. The strength of a transient is defined as the integral of the module of the CWT from the finest scale (corresponding to the maximum frequency) up to a cut off scale a_c (corresponding to a cut off frequency f_c):

$$\delta(b) = \int_{a_{\min}}^{a_c} |CWT_x(a, b)| da \quad (3)$$

The resulting criterion reflects both the instantaneous bandwidth and the signal power. The higher the criterion is, the greater the energy in the upper section of the spectrum and the more transient the signal. And the more transient is the signal the more likely it is to reflect the occurrence of a fracture. The phenomenon was analyzed by plotting the function δ for all the PZT for each impact test as a function of the translation integer b . b is the translation of the wavelet and consequently is equivalent to time. The criterion and the rib fracture occurrence are then correlated in order to set up a threshold. Anytime the criterion overruns the threshold level T , a fracture occurred. The values of the threshold T and the parameter a_c which delimits the low and high frequencies were determined so that the value of $\delta(b)$ was greater than T when a fracture was detected.

3 Results

It was noted that the PZT on Left Rib 3 malfunctioned during all tests. The LR3 signal was therefore removed from the analysis. Figure 2 shows an example of how the criterion successfully

discriminates fracture occurrence. On one hand time-history signals fail to indicate that a fracture occurred on upper chest impact (fig 2b) and no fracture on shoulder impact (fig 2a). On another hand transient criterion clearly indicates that a fracture occurred during the upper chest impact (fig 2d) whereas no fracture occurred during shoulder impact (fig 2d). The threshold was set at 1 in order to discriminate occurrence of a fracture.

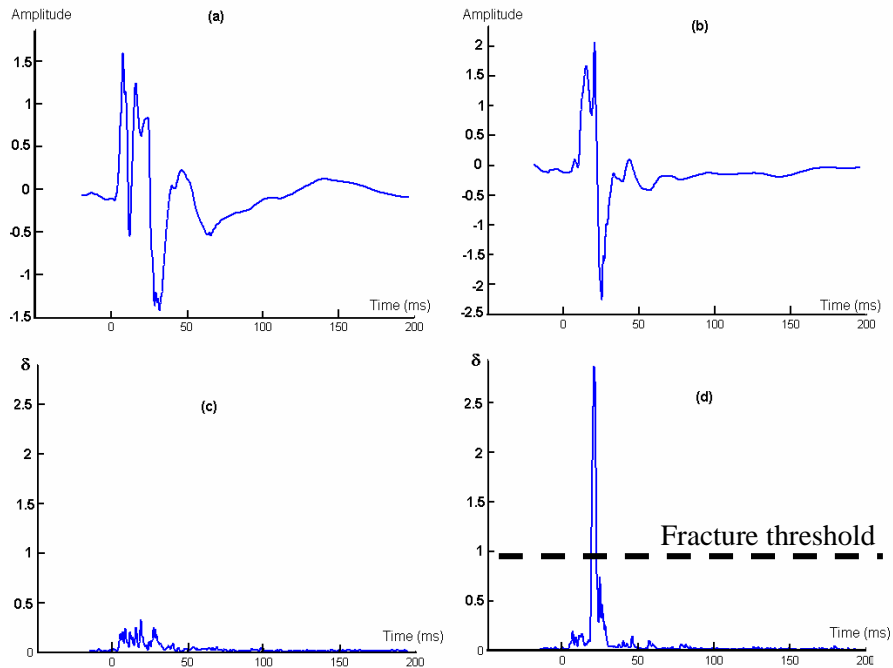


Figure 2: transient criterion successfully discriminates a fracture occurrence illustrated by right rib 3 PZT on right shoulder impact (time history signal (a) / transient criterion (c)) and right rib 3 PZT on upper chest impact (time history signal (b) / transient criterion (d))

	Right side			Left side		
	S	U	M	S	U	M
Test #	1	2	3	4	5	6
PZT RR3	-	fracture	fracture	-	fracture	fracture
PZT RR7	-	-	fracture	-	-	-
PZT LR7	-	-	fracture	-	fracture	fracture
Palpated fractures	-	Right rib 4	Right rib 7	-	Left ribs 3, 4	Left ribs 7,8,9
Fractures non detected during palpation	Right rib 6 , Right rib 9, Left rib 5					

Table 1: successful fracture detection with a_c corresponding to 1145Hz and fracture threshold = 1

Table 1 shows the ability of the criterion to discriminate whether a given impact produces rib fracture. Cut off scale was set to represent a cut off frequency of 1145Hz and fracture threshold was set to 1. Therefore the Right Rib 3 PZT detected a fracture for all the impacts except for the shoulder impacts. The Right rib 7 PZT detected a fracture for right mid chest impact when it gets broken and no fracture elsewhere. Finally, the Left Rib 7 PZT detected a fracture during the left upper chest impact and a fracture on the left mid chest impact when it gets broken.

4 Discussion

4.1 Fracture detection

Several successive impact tests were realized on a thorax, the ribs being instrumented with PZT. The injury report from the necropsy shows that a physician can easily miss non displaced fracture during palpation and that it is therefore critical to have a tool that has a high success in fracture rib detection. The results of the present study showed that a methodology using PZT and time scale representation can be utilized to determine whether a given impact produces rib fracture.

A major improvement compare to the gauge-based method is the ability to detect a fracture even if it occurred on a non instrumented rib. Indeed the gauge needs to be on the rib broken and moreover very close to the fracture location. Therefore 20 PZT at most would be enough to lessen the risk of missing a fracture whereas more than 100 gauges are necessary to reach the same goal [5][6]. Ongoing work is being conducted to determine how to reduce the number of PZT while detecting all the fractures.

4.2 PZT location

For the subject used in this study, the fractures occurred on the anterior section of the rib, posterior to the PZT location. After fracture, the PZT remained attached to the short rib segment connected to the sternum. From table 1 one could notice that once an instrumented rib is broken the PZT attached to it loses the ability to detect a fracture on an adjacent rib.

Two explanations are proposed to explain this behaviour. First, once the fracture has occurred, the stiffness of the rib is greatly reduced. Therefore its ability to transmit high frequency waves decreases. Second, it is suggested that the transient signal generated by the fracture travels through the posterior rib and the spine, and not through the sternum. Indeed the sternum is mainly made of cartilage that behaves as a damping material and could act as a low pass filter. On the contrary the spine, especially on an erected subject, provides a stiffer structure than the sternum for wave propagation: the i th rib attaches to the i th and $i+1$ th vertebra through the superior and inferior costal facet. Besides the facet joints have very little cartilage. Consequently it is recommended to affix the PZT to the most posterior part of the rib. In this way PZT should maintain their ability to detect fracture on close rib after fracture of the rib they are fixed on.

4.3 Limitations

A limitation to the study is that the criterion and the threshold could be very subject specific. The energy measured at time of the fracture depends not only on the position of the sensors on the rib (a sensitivity analysis is required to estimate the influence of the PZT location on the measured signal) but also on the mechanical properties of the rib material and surrounding soft tissues, properties that are subject-dependent. Thus the threshold that was determined from our methodology might be subject dependant. Further analysis of the fracture process is required to better describe the link between the physics of the fracture process and the signal measured by the PZT.

5 Conclusion

This study introduces a novel methodology to determine rib fracture occurrence in impact biomechanics testing. Contrary to the common method that relies on time-history analysis of strain-gauge data, the proposed method uses an in-depth analysis of the sensor signal frequency content based on time-scale analysis. This new method which requires fewer sensors than the strain gauge-based method shows promising results by its capability to detect fracture even though it did not happen on an instrumented rib. The parameter a_c and the threshold need to be adjusted. The proposed method demonstrates the capability of time scale signal processing to characterize a transient signal within a time signal and thus a way to detect rib fractures with a small number of sensors.

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