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Development of wearable haptic interfaces for impact detection on UAV wing structures

* Myung Jun Lee [1)] Hwee Kwon Jung [2)] and Gyuhae Park[3)]

[1), 2), 3)] *School of Mechanical Engineering ,Chonnam National University, Gwangju, Korea*
[3)] *gpark@chonnam.ac.kr*

ABSTRACT

This paper presents development of a haptic interface system for impact localization and assessment. This research utilizes the tactile sense of humans to “feel” impact responses of UAV wing structures. In addition, this approach could capitalize on human’s decision and classification capabilities for such applications. Both hardware and software components are developed for the haptic interface system. Piezoelectric sensors are deployed in a specific L-shape to detect impact events and measure subsequent structural responses. Unique haptic feedback signals are then generated based on measured and pre-processed data, and are wirelessly transmitted to human arms in the form of vibro-haptic stimulation. Several experiments are carried out to demonstrate the performance of the haptic interface, including human training. Results of the experiments shows that humans can detect and “feel” impact events only using haptic feedback signals and improve the impact detection process. Future research will focus on applying this haptic interface for evaluating potential damage caused by impacts.

INTRODUCTION

Structural health monitoring (SHM) is the process of measuring the dynamic response of a system and determining the current state of the system’s health from these data. Current paradigms of SHM or structural dynamics research efforts have focused on developing techniques that autonomously monitor and diagnose a structure’s health state. While many methodologies have been developed, these methods typically do not use human judgment and adaptivity during the monitoring process. However, human classification capabilities exceed those of contemporary classification algorithms [1], and are capable of better adapting to new situations. Therefore in this study, we propose to adopt a new semi-autonomous SHM paradigm in which novel human-machine interfaces are used to leverage computational precision and human adaptability and classification capabilities. Our focus for this study is impact detection of airplane wings, which may cause significant problems during operation.

[1)] Graduate research assistant
[2)] Graduate research assistant
[3)] Professor

CONCEPT OF SHM WITH HAPTIC INTERFACE

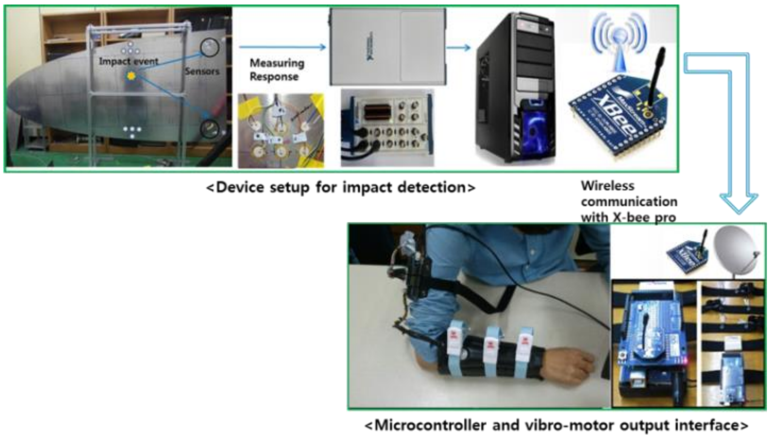

Figure 1.haptic based impact detection

The impact detection scheme with haptic interface used in this study is shown in Fig. 1. Three key features, this system will be required to identify are i) impact detection, ii) impact location and iii) impact intensity. Piezoelectric sensors are deployed to measure the high-frequency waves caused by impact events. The measured data are processed by an on-board computer. Unique haptic signals are then generated and wirelessly transmitted to the haptic interface which is connected to a human arm.

In this study, the processes for haptic-based decision making process are divided into two levels; Level 1 and Level 2. Level 1 haptic is defined as that all the necessary signal processing is carried out by a computer and only the result of computation is delivered to human arms via haptic interfaces. In Level 2 haptic, only pre-processed data are delivered using haptic interface, and human will make a decision based on this delivered information. In this study, the impact detection and localization are carried out by Level 1, and result confirmation and impact intensity estimation are done by Level 2. In this approach, human can compare the results of Level 1 and Level 2 and then determine whether computer's result is reliable or not in order to improve the detection capability. These Level 1&2 haptic processes are integrated in this study for efficient impact detection.

IMPACT DETECTION METHEOD ON ANISOTROPIC PLATES

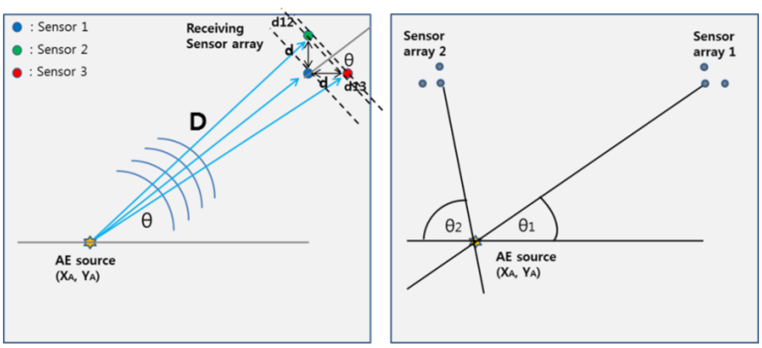

Figure 2. Source localization method using L-shape sensor array

The source localization method developed by Kundu et al[2] was used to detect impact in this study. This method can localize an acoustic source in an anisotropic plate with the help of only six receiving sensors. It also does not require the direction dependent velocity profile in the plate or any need to solve a system of nonlinear equations.

$$\theta = tan^{-1}(\frac{\Delta t_{12}}{\Delta t_{13}}) \qquad (1)$$

From Eq. (1), the wave propagation direction and the wave velocity in that direction are obtained in terms of experimentally measured values t_{21} and t_{31} where td21 is time difference of arrival between sensor 1 and 2 and td31 is time difference of arrival between sensor 1 and 3. Once angle θ_1 is estimated, angle θ_2 can be estimated with the same procedures. Source location is then obtained using the two estimated angles. Because this method does not require a wave velocity profile, we can get accurate results even on anisotropic plates or complex shaped structures.

VIBRO-HAPTIC INTERFACE SYSTEM FOR IMPACT DETECTION

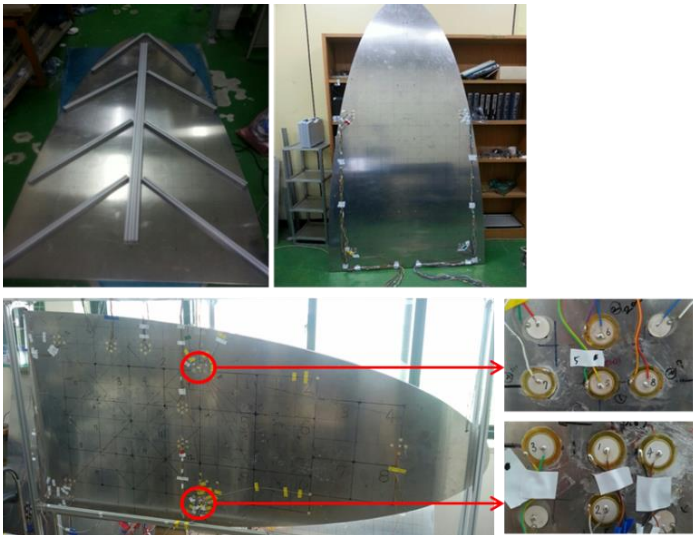

Figure 3. Wing shape structure

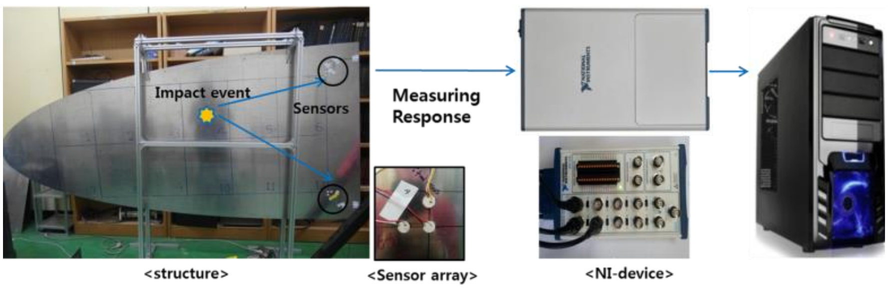

Figure 4. Experiment set up for impact detection on a wing shape structure

A 1200mm by 2400mm wing shaped structure was built for experiments. Two sensor clusters were then installed at the top and bottom of the structure. NI-6366 was used for measurements with a sampling of 2 MHz. Then a haptic interface aims to capitalize on the human sense of touch to provide information of impact situation. This haptic interface is equipped with a vibro-motor array, microcontroller and wireless communication system. As shown in Fig. 5, 12 vibro-motor positions are corresponding to 12 impact sections.

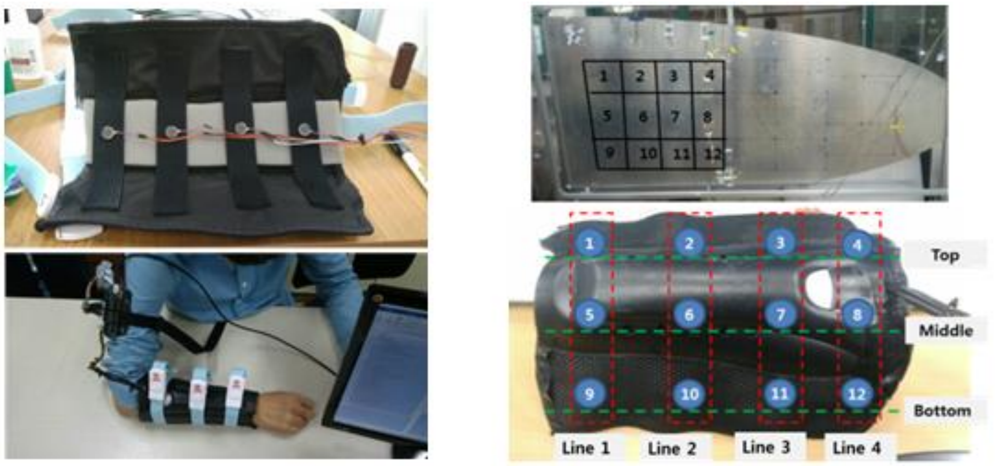

Figure 5. Arm wearable output interface

A microcontroller (Arduino 2560) is used to operate haptic actuators individually. After haptic signals are generated, a pair of wireless telemetry (X-bee pros) is used to transmit haptic signals to the arm wearable haptic interface.

HUMAN TRAINING AND TEST

1) Human training and performance test protocol

Human training and tests were implemented to demonstrate the performance of the proposed haptic interface impact detection system. Total 8 people took part in human training and performance test as a novice. 3 people were then chosen for the expert group and took additional training. The test supervisor controls the training and testing from impact detection interface, allowing them to send various impact cases to haptic interface or stop all interface vibrations if necessary.

The performance test consists of individual haptic signal tests and overall haptic signal tests. Various impact signals were measured for test of overall haptic signal. This test was conducted over 15 times

2) Results of training and test

Trainee number		Total training time	Impact localization	Result confirmation	Subsequent damage assessment
1	Novice	44 minute	93.33 %	86.67 %	100 %
	Expert	15 minute	100 %	95 %	100 %
2	Novice	28.5minute	96.67 %	90 %	100 %
	Expert	23minute	99 %	99 %	100 %
3	Novice	42 minute	93.33 %	73.33 %	100 %
	Expert	34 minute	95 %	98 %	100 %

Table 1. total training time and performance of expert group

Test results are shown in Table 1. For step 2 (Impact localization, Level 1 haptic) the average accuracy was 94%, and, for step 3 (Impact localization, Level 2 haptic) the average accuracy was 87.5%. For impact intensity estimation (step4), all but one trainee gets 100% accurate. The most difficult part of training and the associated results are for step 3. However, even with relatively lower accuracy, trainees identified neighboring sections of actual impact locations.

One remarkable result to point out is that, more than a few occasions, trainees could notice signal abnormalities by feeling improper haptic signals. Usually these signals are caused by low signal to noise ratio, improper impact excitation, or DAQ failure. An algorithm processes this data without having any cleansing process and leads false indications of the structural impact condition. However, by using haptic interface which capitalizes on human reasoning capacities, this types of false indications on structural condition could be drastically reduced, which may be a clear advantages of the proposed technique.

CONCLUSION

In this study, a new SHM paradigm for detecting impact events on structures by using haptic interface is introduced. Distributed sensors, computer algorithms, and human classification capabilities are integrated for efficient impact detection. Both software and hardware components are developed, focusing on applications in aerospace structures. Piezoelectric sensors are deployed in an L-shape for impact localization and a haptic interface was designed to generate and transmit haptic signals to humans. After human training, a human could detect impact events, location, and intensity only using a haptic interface with relatively good accuracy. Also measurement errors and algorithm failures of sensing systems could be identified by improper haptic signals.

ACKNOWLEDGMENT

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