Structural Dynamic Response Compressing Technique in Bridges using a Cochlea-inspired Artificial Filter Bank (CAFB)

G Heo¹, J Jeon¹*, B Son¹, C Kim², S Jeon², C Lee²

¹Department of Civil Engineering, Konyang University, 121 Daehangro, Nonsan, Chungcheongnam-do, South Korea
²Department of Civil Engineering, Chungnam National University, 99 Daehangno, Daejeon, South Korea

*Corresponding author: jrjeon@konyang.ac.kr

Abstract. In this study, a cochlea-inspired artificial filter bank (CAFB) was developed to efficiently obtain dynamic response of a structure, and a dynamic response measurement of a cable-stayed bridge model was also carried out to evaluate the performance of the developed CAFB. The developed CAFB used a band-pass filter optimizing algorithm (BOA) and a peak-picking algorithm (PPA) to select and compress dynamic response signal containing the modal information which was significant enough. The CAFB was then optimized about the El-Centro earthquake wave which was often used in the construction research, and the software implementation of CAFB was finally embedded in the unified structural management system (USMS). For the evaluation of the developed CAFB, a real time dynamic response experiment was performed on a cable-stayed bridge model, and the response of the cable-stayed bridge model was measured using both the traditional wired system and the developed CAFB-based USMS. The experiment results showed that the compressed dynamic response acquired by the CAFB-based USMS matched significantly with that of the traditional wired system while still carrying sufficient modal information of the cable-stayed bridge.

1. Introduction
Structural health monitoring (SHM) systems were intensively studied in the 1990s. Since then, the SHM system was actively applied to long-span bridges in advanced countries such as Europe, the U.S., and Japan as well as in the emerging countries such as Canada, Korea, and China. Some notable studies on long span bridges were applied to Bill Emerson Memorial Bridge of the U.S. [1] (Celebi, 2004), Hakurho Bridge of Japan [2] (Abe, 2000), Great Belt East Bridge of Denmark [3] (Andersen, 1994), Seoha Bridge of Korea [4] (Yun, 2003), and Tsing Ma Bridge of Hong Kong [5] (Wong, 2004). The SHM systems are expected to be applied to more bridges and civil infrastructures over the world. Even though the conventional SHM systems are actively engaged in structural health monitoring and damage detection of civil structures, they still need to be developed more in regard to the aspects of installation and maintenance as follows. First, a wired measurement system costs a lot for its initial installation especially when expanding measurement channels. Next, increased measurement channels require additional management resources to handle tremendously numerous response data. Such limitations in installation and maintenance eventually need to be tackled as SHM operates on lengthy measurements over time. For this, Spencer (2004) [6] and Lynch (2006) [7] introduced the WSN-based smart SHM (S-SHM) system to the construction sector. Another noteworthy study of an S-SHM is done by Kurata, et. al [8] (2012) who developed a wireless sensor...
Narada that is able to charge itself by using solar panels and an inter-sensor node sub-network. Although such a S-SHM system has some shortcomings in power consumption and efficiency and robustness of the wireless network, it is anticipated to be continuously developed improving its mobility, install-ability, low installation cost, and low maintenance cost [9] (Heo, 2009).

In structural health monitoring it is important to measure significant dynamic (acceleration) responses of structure. However, dynamic response data are usually much more than static response ones, and the data size of response measurements taken via WSNs are limited within the performance specifications of the radio frequency (RF). To fulfill the former requirement, Peckens, et al [10] (2013) proposed a cochlea-inspired wireless sensor nodes that make it possible to decrease cost and increase efficiency. The developed wireless sensor node is composed of a CPU and a memory embedded base board, a cochlea-inspired neuron board, and a radio interface board for wireless communication. However, their studies still carry some unresolved issues. First, a CPU and a memory embedded baseboard are comparatively cheap yet functions well while making use of the parts already in production, but their performance gets slow when the sampling rate increases for improving accuracy of data or when the number of input channels also increases for handling large sized data. Second, although neuron boards were already tested and approved for implementation on analog filter banks, they need to be redesigned and remanufactured whenever a new structure comes up.

This study proposes a new data compressing technique based on a digital method. Also a cochlea-inspired artificial filter bank (CAFB) based on a band-pass filter optimizing algorithm and peak-picking algorithm was developed in order to filter for the significant range of dynamic responses and efficiently compress filtered results. The developed CAFB was optimized using the El-Centro earthquake wave often used for studies in the field of construction, and the CAFB was implemented via a wireless measurement system. Also a modal test was performed on a cable-stayed bridge model for an analysis of its dynamic characteristics. Lastly the results were compared to those of wired measurement system.

2. Cochlea-inspired Artificial Filter Bank (CAFB)

2.1. Concept of CAFB

A data compression technique is necessary to efficiently attain the dynamic responses of a structure based on WSNs with limited wireless bandwidth. A key point in achieving a compressive technique is that dynamic characteristics of the original signal must be well reflected in the compressed signal as it was the same for the filter bank. Based on many design factors and conditions, this study developed a CAFB using a band-pass filter optimizing algorithm (BOA) for filter bank configuration, and also a peak-picking algorithm (PPA) for data compression. Figure 1 is the conceptual diagram of the CAFB developed in this study for obtaining dynamic responses of structures.

2.2. Band-pass filter optimizing algorithm (BOA) and peak-picking algorithm (PPA)

An artificial filter bank is for an efficient acquisition of dynamic responses of a structure. This study develops the one that uses a BOA and a PPA. For the BOA, multiple band-pass filters are designed in parallel to determine a required target mode for evaluating the dynamic characteristics of a structure, and the design parameters such as number, bandwidth, and spacing of band-pass filters are recursively modified to create the reconstruction signal. The reconstruction effect was evaluated by comparing the result to the raw data obtained from the structure. The following equation (1) was used to calculate reconstruction error (RE) for evaluating the reconstruction effect of reconstruction signal.

\[
RE = \frac{\int_T |u(t) - y(t)|}{T}/|u(t)|
\]

Where \(u(t)\) is the raw signal in response time, \(y(t)\) is the reconstruction signal in response time, and \(T\) is the total length of response period. The reconstruction effect becomes greater as the reconstruction error gets closer to zero.
Next the PPA selects peak values from the reconstruction signals determined by equation (1) through resampling, and peak values are selected only when there is a sign change while calculating the slope of each sample signal. The resulting compressive signal is then transmitted via WSNs to the data administrator, and the compressive ratio (CR) equation (2) is used to evaluate compressive efficiency of the resampled compressive signal.

$$CR = \frac{N_{S_C}}{N_{S_O}}$$  \hspace{1cm} (2)

$N_{S_C}$ is the number of compressive samples while $N_{S_O}$ is the number of samples from reconstruction signal. The closer the CR gets to zero, the better the compressive efficiency becomes.

![Cochlea-inspired Artificial Filter Bank (CAFB)](image)

**Figure 1.** Concept of cochlea-inspired artificial filter bank (CAFB) for SHM

3. Optimizing and Programming of CAFB

3.1. Optimal design of CAFB

A CAFB was developed in section 2 to efficiently obtain the dynamic responses of structures. In this section the developed CAFB is optimally designed for random signals, and its performance and validation are evaluated from a numerical simulation of optimum CAFB. This study chose El-Centro earthquake wave as the input signal to numerically evaluate the performance of the developed CAFB. Figure 2 shows the time and frequency responses of El-Centro used as the input signal.

![Time domain of El-Centro wave](image)

(a) Time domain of El-Centro wave
The frequency range of target mode required for structural health monitoring is limited to less than 10Hz because normally long and large structures in the construction sector pertain to slow dynamics. Therefore, the frequency range of interest was selected less than 10Hz for the BOA of the artificial filter bank, and the number of band-pass filters was selected as ten. The selected frequency range of interest generally applies to long and large structures which are also often common facilities. The number of band-pass filters is arbitrarily selected because they become optimized during the BOA computations. Table 1 and Figure 3 are reconstruction errors (RE) calculated using equation (1) while considering the assumed band-pass filter number is 10 and the selected frequency range of interest is below 10Hz. Reconstruction errors are calculated for 100 cases by increasing the bandwidth and spacing of band-pass filters by 0.1Hz between 0 and 1Hz. From Table 1 and Figure 3, the reconstruction error is minimized at a bandwidth of 0.6Hz and spacing of 1.0Hz for the filter bank with an initial filter bank number of 10. Selected bandwidth and spacing are determined as the optimal condition for BOA.

Table 1. Reconstruction error (RE) for a filter bank with 10 filters

| Bandwidth of filters (Hz) | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
|--------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1.0                      | -   | 0.19930 | 0.16497 | 0.13378 | 0.10931 | 0.09347 | 0.08713 | 0.09036 | 0.10278 | 0.12373 | 0.15250 |
| 0.9                      | -   | 0.19515 | 0.15896 | 0.12816 | 0.10692 | 0.09705 | 0.09893 | 0.11214 | 0.13588 | 0.16920 | 0.21118 |
| 0.8                      | -   | 0.19374 | 0.15711 | 0.12810 | 0.11125 | 0.10870 | 0.14650 | 0.18474 | 0.23406 | 0.29320 | x     |
| 0.7                      | -   | 0.18970 | 0.15631 | 0.13387 | 0.12719 | 0.13762 | 0.16462 | 0.20688 | 0.26290 | 0.33124 | 0.41053 |
| 0.6                      | -   | 0.18396 | 0.14814 | 0.13360 | 0.14171 | 0.17114 | 0.21986 | 0.25853 | 0.36719 | 0.46229 | 0.56957 |
| 0.5                      | -   | 0.18357 | 0.14861 | 0.14443 | 0.17345 | 0.23217 | 0.31612 | 0.42141 | 0.54484 | 0.68378 | x     |
| 0.4                      | -   | 0.19240 | 0.17890 | 0.21053 | 0.28428 | 0.39277 | 0.52962 | 0.68971 | x     | x     | x     |
| 0.3                      | -   | 0.19745 | 0.21661 | 0.29817 | 0.42797 | 0.59387 | 0.78741 | x     | x     | x     | x     |
| 0.2                      | -   | 0.23026 | 0.29689 | 0.42203 | x     | x     | x     | x     | x     | x     | x     |
| 0.1                      | -   | 0.25073 | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| 0.0                      | -   | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |

As a last step in the optimum design of the CAFB, this study determined the number of band-pass filters based on the optimally selected bandwidth (0.6Hz) and spacing (1.0Hz) of the band-pass filters. The reconstruction error and compressive ratio were calculated against the different number of band-pass filters. The calculated RE and CR are shown in Figure 4, and the results are tabulated in Table 2 along with peak-picked values. Figure 4 shows that RE and CR have an inverse relationship, and the optimum number of band-pass filters are determined to be 6, where the relative difference between RE and CR is at a minimum. Also table 2 shows that the size of the compressed data with band-pass filter number 6 is 312, which gives more efficient compression effectiveness compared to compressed data size 424 of the initially assumed band-pass filter number 10. Conversely, the reconstruction effectiveness becomes slightly decreased.

(b) Frequency domain of El-Centro wave

Figure 2. Reference signal (El-Centro earthquake wave) for optimal design of CAFB
Table 2. Optimization of number of filters (reconstruction error (RE) vs. compressive ratio (CR))

| No. of Filters | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RE             | 0.2108 | 0.1997 | 0.1792 | 0.1571 | 0.1366 | 0.1289 | 0.1222 | 0.1072 | 0.0965 | 0.0871 |
|                | 0.0808 | 0.0732 | 0.0694 | 0.0630 | 0.0605 | 0.0545 | 0.0516 | 0.0489 | 0.0473 | -    |
| CR             | 0.1000 | 0.0952 | 0.0992 | 0.1080 | 0.1160 | 0.1248 | 0.1368 | 0.1480 | 0.1600 | 0.1696 |
|                | 0.1768 | 0.1872 | 0.1944 | 0.2000 | 0.2008 | 0.2040 | 0.2008 | 0.2056 | 0.2136 | -    |
| No. of Peak-p’s| 250  | 238  | 248  | 270  | 290  | 312  | 342  | 370  | 400  | 424  |
|                | 442  | 468  | 486  | 500  | 502  | 510  | 502  | 514  | 534  | -    |
3.2. Programming of CAFB

The designed CAFB was optimized around the El-Centro earthquake, and the optimization gave six for the number of band-pass filters, 0.6Hz for the frequency range, and 1.0Hz for frequency spacing. Figure 5 shows the logic of developed CAFB, and the CAFB was programmed via Matlab M-code for its implementation in the wireless sensing system in chapter three.

Figure 5. S/W programming and CAFB embedded for unified structural management system

Figure 5(a) shows a logic for synchronized data measurement through active channels, and figure 5(b) shows a channel selecting logic, while figure 5(c) shows the logic for transmitting data obtained in figure 5(a) and 5(b) to the host. Figure 5(d) gives a logic for multi-channel expansions, while Figure 5(e) shows a logic for embedding the CAFB optimally designed in the previous study into the system. The developed logics in figure 5 were all programmed in Labview, and they were used for the administrative software of the unified structural management system (USMS) put together in chapter three. The CAFB optimally designed in figure 5(e) was programmed in Matlab M-code, and it was limitedly embedded into acceleration measurement channels among the multi-channels.

3.3. CAFB-based unified structural management system (USMS)

This paper develops a unified structural management system (USMS) based on digital-software-design (D-SW-D), which is aimed to overcome the shortcomings of the traditional wired system (complex cable lines, excessive installation cost, and continued maintenance on-site), to improve the limits of wireless system (limited performance of sensor nodes, analog implementation of logics, low velocity and short range communication), and to fully implement digitally developed data compressing technique developed in the previous study. The USMS consists of a logger and controller system (L&CS) in figure 6(a), a multi input and output system (MIMOS) in figure 6(b), a two-way wireless communication system (TWCS) in figure 6(c), and a central monitoring and control system (CMCS) in figure 6(d).
4. Experimental Estimation of CAFB-based USMS

4.1. Cable-stayed bridge model
The model structure used for experiments is a cable-stayed bridge which is almost representative of bridge structures. As seen in figure 7 and table 3, the cable-stayed bridge model was built by scaling down the Seohae Grand Bridge of South Korea by 1 to 20. And it was designed to have a target mode (natural frequency) below 10Hz to reflect the flexible dynamic characteristics of cable-stayed bridges. The response of cable-stayed bridge model was also concurrently measured using the conventional wired system for a comparison with the wireless USMS for the accuracy of obtained data.

Figure 7. View of cable-stayed bridge model
Table 3. Design dimensions of cable-stayed bridge model

| Category                        | Dimensions                        |
|---------------------------------|-----------------------------------|
| Total / main span length        | 4.22m / 2.22m                     |
| Superstructure width / Tower heights | 0.17m / 1.00m                   |
| Tower boundary conditions       | Roller and hinge                  |
| Bridge end boundary conditions  | Roller                            |
| Bridge material                 | Structural steel                  |
| Cable material                  | Spring (K=1.03N/mm)               |
| Concentrated load               | 1kg (39EA)                        |

4.2. Modal Test of Cable-stayed bridge model

To evaluate the CAFB-based USMS, this study executes modal experiments using both the developed system and the wired measurement one. The measurement location of the wired and the wireless system was chosen at 1/3 of the main span on the girder for acquiring acceleration responses in a vertical direction. Figure 8 is the wired and the wireless measurement system respectively, and the wired measurement system used was Model: 652U from iO-tech and ME'Scope from Vibrant Tech.

Figure 8. Wired measurement system and wireless measurement system (USMS)

(a) Wired measurement system
(b) Wireless measurement system (in CAFB)

Figure 9. Time and frequency response using wired measurement system

(a) Time domain of wired measuring data
(b) Freq. domain of wired measuring data

Figure 10. Time and frequency response using wireless measurement system (USMS)

(a) Time domain of wireless measuring data
(b) Freq. domain of wireless measuring data

Figure 9 and figure 10 show the measured raw data from the wired and the wireless dynamic measurement system in both a time domain and a frequency domain while table 4 summarizes the natural frequency of both data. The wireless measurement results showed an error of only 0.036 ~ 2.471% compared to those of the wired system, confirming the validity of USMS set up in this study.
### Table 4. Comparison of modal test results of cable-stayed bridge model

| Bending mode | Wired (Hz) | USMS (Hz) | Error (%) |
|--------------|------------|-----------|-----------|
| 1<sup>st</sup> | 2.735      | 2.736     | 0.036     |
| 2<sup>nd</sup> | 4.005      | 4.104     | 2.471     |
| 3<sup>rd</sup> | 6.154      | 6.058     | 1.559     |

4.3. Estimation of a CAFB

This chapter focuses on a quantitative evaluation of the CAFB using a reconstruction error of equation (1) and a compressive ratio of equation (2). The study designed and implemented the peak-picking algorithm (PPA) within the CAFB to compress data for efficient management and control of the wireless communication and measurement database. The peak values are compared to the reconstruction signal and original signal in both time and frequency domains in figure 11. Figure 11(a) shows that the PPA picks out the peak values of reconstruction signal, and figure 11(b) shows that the peak signal accurately purveys the modal information. Therefore, the PPA was proven effective in drawing out peak values that contain the modal information from the reconstruction signal.

![Figure 11](image)

(a) Time domain response (original vs. reconstruction vs. peak-picking signal)

(b) Freq. domain response (original vs. reconstruction vs. peak-picking signal)

Figure 11. Comparison of time and frequency domain of peak-picking signal using USMS

For a quantitative evaluation of CAFB, illustrated in figure 9, this study tabulates eigenvalues, and also its error in the compressive signal and the reconstruction signal in contrast to the original signal in Table 5. Also the reconstruction error (RE) is compared to the reconstruction signal against the original signal, and the compressive ratio (CR) is also compared to the compressive signal against the in Table 6. In Table 5, it is found that the reconstruction signal shows 0% error in eigenvalues compared to that of the original signal while the compressive signal shows error under 2.5%, which means the modal information of the raw signal are significantly reflected in the compressive signal. Table 6 also shows RE and CR of 0.4461 and 0.095 respectively, meaning 55.39% of reconstruction effectiveness and 90.5% data compression.
Table 5. Modal results of compressive, reconstruction, and original signal

| Bending | Wireless (Hz) | Reconstructed (Hz) | Error (%) | Peak_p (Hz) | Error (%) |
|---------|---------------|-------------------|-----------|-------------|-----------|
| 1<sup>st</sup> | 2.736 | 2.736 | 0.000 | 2.735 | 0.036 |
| 2<sup>nd</sup> | 4.104 | 4.104 | 0.000 | 4.005 | 2.412 |
| 3<sup>rd</sup> | 6.058 | 6.058 | 0.000 | 6.057 | 0.016 |

Table 6. Performance (reconstruction and compression effect) of CAFB

| RE | Reconstruction efficacy (%) | CR | Compressive efficacy (%) |
|----|-----------------------------|----|--------------------------|
| 0.4461 | 55.39 | 0.095 | 90.5 |

5. Conclusion

This study developed an artificial filter bank using a digitally implemented band-pass filter optimization algorithm (BOA) and a peak-picking algorithm (PPA), and also evaluated it via a numerical simulation in order to efficiently obtain the significant dynamic (acceleration) responses in real time for structural health monitoring of structures. The developed CAFB was optimized using the El-Centro earthquake wave often used for studies in the field of construction, and the CAFB was implemented via a wireless measurement system. Also a modal test was performed on a cable-stayed bridge model for an analysis of its dynamic characteristics. Lastly the results were compared to those of wired measurement system. The followings are concluded from the experimental evaluation of the developed CAFB:

- The band-pass filter optimizing algorithm of CAFB was effectively able to concentrate on the signals only within the specific frequency range, out of the random signals with a wide frequency range. And the peak-picking algorithm of CAFB was found valid as a data compressing technology because it can resample the dynamic response by picking only the peak values that contain significant modal information.

- The CAFB was also found to have a capacity of obtaining effective dynamic (acceleration) responses compressed within a specific frequency range, and it was proven a new measurement technology applicable for a WSNs-based structural health monitoring system which has recently attracted attention.

- Ultimately the S/W design-based CAFB developed in this study improves all the shortcomings of the traditional analog filter banks while it efficiently obtains the significant dynamic responses compressed about the frequency range of interest. It is anticipated to provide a new paradigm in the structural health monitoring utilizing wireless sensor networks. The digital filter bank is also expected to provide high practicality and applicability because it can quickly implement new logics, optimizations, and design within a software.

References

[1] Celebi M, Purvis R, Hartnagel B, Gupta S, Clogston P, Yen P, O’Connor J and Franke M 2004 Seismic instrumentation of the Bill Emerson Memorial Mississippi River Bridge at Cape Girardeau (MO): A cooperative effort Proceedings of the 4th International Seismic Highway Conference Memphis Tenn USA

[2] Abe M, Fujino Y, Yanagihara M and Sato M 2000 Monitoring of hakucho suspension bridge by ambient vibration measurement Proceedings of the Nondestructive Evaluation of Highways Utilities and Pipelines IV Newport Beach USA

[3] Andersen EY and Pedersen L 1994 Structural monitoring of the Great Belt East Bridge Strait crossings 94 Krokebogr J (deitor) A.A. Balkema Rotterdam 189
[4] Yun C B, Lee J J, Kim S K and Kim J W 2003 Recent R&D activities on structural health monitoring for civil infra-structures in Korea KSCE Journal of Civil Engineering 7 637

[5] Wong K Y 2004 Instrumentation and health monitoring of cable-supported bridges Journal of Structural Control and Health Monitoring 11 91

[6] Spencer B F, Ruiz-Sandoval M E and Kurata N 2004 Smart sensing technology: opportunities and challenges Journal of Structural Control and Health Monitoring 11 349

[7] Lynch J P and Loh K J 2006 A summary review of wireless sensors and sensor networks for structural health monitoring The Shock and Vibration digest 28 91

[8] Kurata M, Kim J, Lynch J P, van der Linden G, Sedarat H, Thometz E, Hipley P and Sheng L 2013 Internet-Enabled Wireless Structural Monitoring Systems: Development and Permanent Deployment at the New Carquinez Suspension Bridge Journal of Structural Engineering SPECIAL ISSUE: Real-World Applications for Structural Identification and Health Monitoring Methodologies 139 1688

[9] Heo G and Jeon J 2009 A Smart Monitoring System Based on Ubiquitous Computing Technique for Infra-structural System: Centering on Identification of Dynamic Characteristics of Self-Anchored Suspension Bridge KSCE Journal of Civil Engineering 13 333

[10] Peckens C A and Lynch J P 2013 Utilizing the cochlea as a bio-inspired compressive sensing technique Smart Materials and Structures 22 1

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (grant number: NRF-2013R1A2A1A01016192), and funded by the Ministry of Science, ICT & Future Planning (grant number: NRF-2013R1A1A063540).