Structural Health Monitoring Using FFT

Kevin Loewke[a], David Meyer[b], Anthony Starr[a] and Sia Nemat-Nasser*[a]

[a]Center of Excellence for Advanced Materials, Department of Mechanical and Aerospace Engineering, University of California, San Diego, La Jolla, CA, USA 92093-0416;
[b]Department of Mathematics, University of California, San Diego, La Jolla, CA, USA 92093-0112

ABSTRACT

This work is part of an effort to develop smart composite materials that monitor their own health using embedded micro-sensors and local network communication nodes. Here we address the issue of data management through the development of localized processing algorithms. We demonstrate that the two-dimensional Fast Fourier Transform (FFT) is a useful algorithm due to its hierarchical structure and ability to determine the relative magnitudes of different spatial wavelengths in a material. We investigate different algorithms for implementing the distributed FFT and compare them in terms of computational requirements within a low-power, low-bandwidth network of microprocessors.

Keywords: Fast Fourier Transform, FFT, Structural Health Monitoring

1. INTRODUCTION

Composite materials have found a wide range of applications in engineering due to their high strength-to-weight ratio, resistance to fatigue, and low thermal expansion. Composites present challenges for damage detection, however, since much of the damage often is interlaminar and not readily detectable.[1] Furthermore, inspection usually takes place after the damage has already occurred, leaving the inspection process to look for residual signs of the failure condition. There is therefore a current need to develop real time and *in situ* health monitoring techniques that enable a rapid assessment of material's state of health.

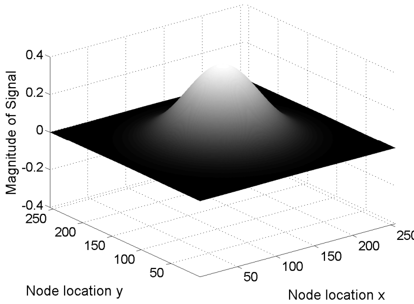
There have been a number of efforts aimed at incorporating non-structural elements into composite materials for damage detection and assessment.[2–4] The work described here is part of an ongoing effort to develop a new type of smart composite material that monitors its health using embedded micro-sensors and local network communication nodes.[5,6] Integrating such devices will allow the material to internally acquire and process structural information. Unlike global networks that allow only one transmission at a time, local networks exchange information locally between nodes, and allow an increase in total instantaneous bandwidth at the expense of reduced reach. Some of the challenges involved in this project include mechanical integration, electronics requirements and limitations, and sensor selection. This paper addresses the issue of data management.

As the number of sensor nodes increases, the ability to efficiently manage data becomes an important issue. For large structures, shuffling the data from the embedded network to an external processor would require unreasonable bandwidth. Furthermore, we want to take advantage of the available high instantaneous bandwidth within the local network. It is therefore necessary to develop efficient localized processing algorithms that are hierarchical in structure and can be easily distributed across the network. This research investigates the implementation of the two-dimensional Fast Fourier Transform (FFT) as one such algorithm. The 2D FFT essentially decomposes a discrete signal into its frequency components (of varying magnitude), and shuffles the low frequency components to the corners. That is, it reveals the relative magnitudes of different spatial wavelengths in a material. This may be applied, for example, to determine the global components of a strain field or temperature distribution.

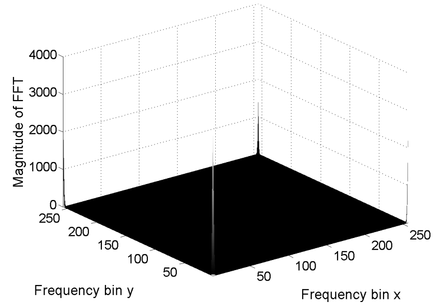
Figure 1 demonstrates the application of the 2D FFT to a simulated signal of size 256×256 that could represent a local peak in temperature in a composite material. The magnitude of the 2D FFT is plotted with

*Contact: E-mail: sia@ucsd.edu; Telephone: (858) 534-4914; Web: ceam.ucsd.edu

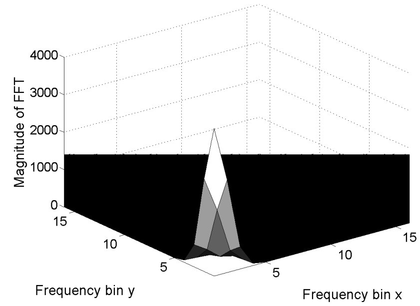
Smart Structures and Materials 2005: Sensors and Smart Structures Technologies for Civil, Mechanical and Aerospace Systems, edited by Masayoshi Tomizuka, Proc. of SPIE Vol. 5765
(SPIE, Bellingham, WA, 2005). 0277-786X/05/$15. doi: 10.1117/12.598827



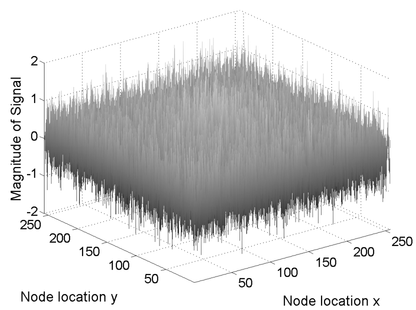
(a) Simulated signal of size 256 × 256.



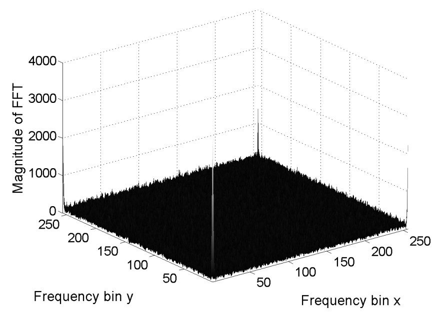
(b) Magnitude of 2D FFT of signal shown in (a).



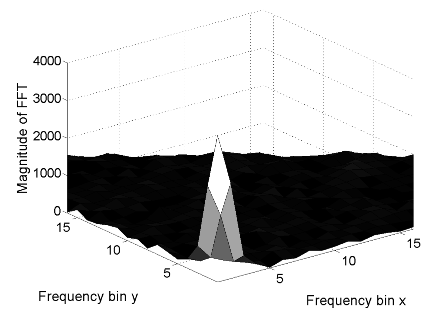
(c) Low-frequency components of 2D FFT of signal shown in (a).



(d) Simulated signal shown in (a) with added Gaussian random noise.



(e) Magnitude of 2D FFT of signal shown in (d).



(f) Low-frequency components of 2D FFT of signal shown in (d).

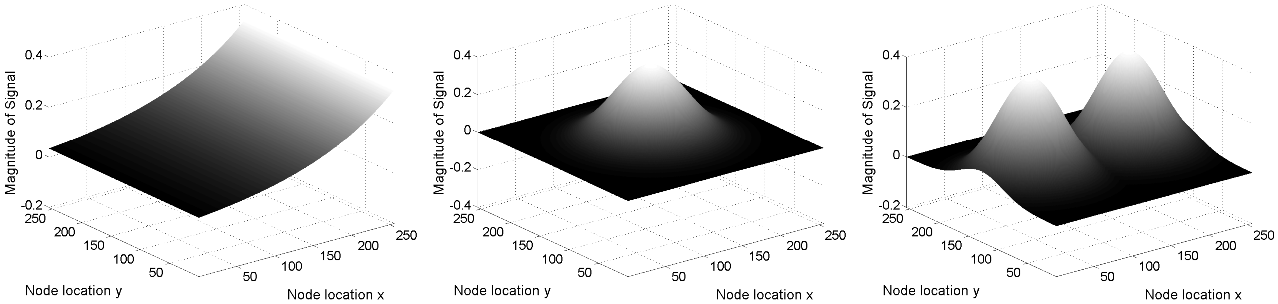
Figure 1. Application of the 2D FFT to a simulated temperature signal of size 256 × 256, with and without added noise. By analyzing only a few output points, we can determine that the signal is dominated in both the x-direction and y-direction by the first frequency components, indicating a temperature peak. These simulations also show that for some situations the 2D FFT is capable of retrieving signals in noisy environments.

respect to spatial frequency. It is immediately clear that the most significant information exists in the lowest frequency components. The zeroth frequency has the largest magnitude, and represents the constant function in the signal. By analyzing only a few other output points, we can determine that the signal is dominated in both the x-direction and y-direction by the first frequency components. This indicates that the signal consists of a single temperature peak, as opposed to several peaks, or a gradient in one direction. Figure 1 also shows that the 2D FFT is capable of revealing these characteristics when Gaussian random noise is added to the signal. Such noise could be attributed to small temperature fluctuations that are the result of atmospheric (or other external) conditions. This property is especially important as most practical monitoring would occur in a noisy environment.

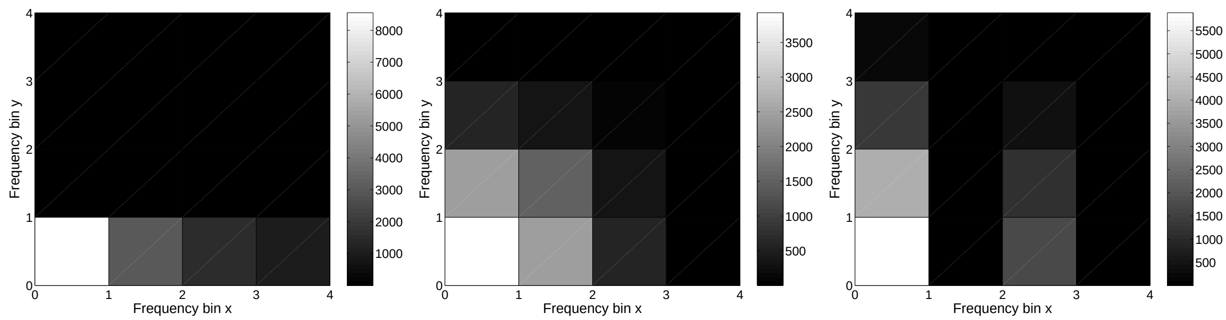
2. 2D FFT ALGORITHMS

The focus of this research is to establish an efficient algorithm for implementing the 2D FFT using a network of nodes embedded within a composite material. The implementation of the 2D FFT using more than one processor has been widely studied.[7–9] In most cases the number of processors is significantly less than the number of input data points, and the 2D FFT algorithms are said to be performed in a *parallel* manner. In this paper, however, we consider the implementation of the 2D FFT using a network where the number of nodes is the same as the number of input data points. We refer to these algorithms as *distributed*.

The 2D Discrete Fourier Transform (DFT) can be efficiently implemented using two different algorithms. The first algorithm, known as the Radix-2 Row-Column FFT, sequentially performs 1D FFTs on each row and



(a) Simulated gradient signal of size 256×256. (b) Simulated single-peak signal of size 256×256. (c) Simulated double-peak signal of size 256×256.



(d) Magnitude of 2D FFT of signal shown in (a), pruned to size 4×4. (e) Magnitude of 2D FFT of signal shown in (b), pruned to size 4×4. (f) Magnitude of 2D FFT of signal shown in (c), pruned to size 4×4.

Figure 2. Application of the 2D FFT to three simulated temperature signals of size 256×256. Only the 4×4 matrix of low frequency components is needed to distinguish between signals that consist of a gradient, one peak, or two peaks.

then each column of the original sequence.[10] The second algorithm, known as the Radix-2×2 Vector-Radix FFT, involves a recursive decomposition of the 2D DFT into sums of smaller 2D DFTs.[11] When implemented on a single processor, the Vector-Radix algorithm requires 25% fewer multiplications than the Row-Column algorithm.[12]

The distributed Row-Column and Vector-Radix algorithms have been derived assuming that all calculations would be distributed across a network of microprocessors.[6] Assumptions regarding the processing capabilities of the low-power, low-bandwidth network are used to evaluate the inter-node communication and calculation requirements. The most significant assumption is that the data sequence $x(k_1, k_2)$, defined over $0 \leq k_1 < N$, $0 \leq k_2 < N$, is acquired and processed by an $N \times N$ array of nodes that can communicate only to nearest neighbors (up, down, left, right). While the Row-Column and Vector-Radix algorithms have identical communication requirements, the Vector-Radix algorithm requires 50% fewer multiplications than the Row-Column algorithm when performed in a distributed manner.[6]

3. PRUNING THE 2D FFT

As shown in Figure 1, the 2D FFT reveals the relative strengths of periodic signals within a composite material. When looking for signals such as large pressure gradients or peaks, the most important information can often be found in the lowest frequency components of the 2D DFT. A significant amount of the output data can therefore be ignored, allowing for modification of the 2D FFT algorithms to improve computational efficiency.

Figure 2 compares the pruned 2D FFT outputs of three simulated temperature signals of size 256×256. By analyzing only a few of the low frequency components of the 2D FFTs, we can easily distinguish between the three signals. Let us consider the gradient signal shown in Figure 2(a). The 2D FFT of the gradient shows that the frequency components in the y-direction have a magnitude of close to zero, indicating that the spatial wavelengths in that direction are relatively constant. The x-direction, however, is clearly dominated by the first frequency component. We can conclude from this information that the signal consists of a gradient in the x-direction. Next let us consider the single-peak and double-peak signals shown in Figures 2(b) and 2(c), respectively. The 2D FFTs of the two signals are similar except for one significant difference: the 2D FFT of the double-peak signal is dominated in the x-direction by the second frequency component rather than the first frequency component. This indicates the presences of two peaks in the x-direction, as opposed to a single peak.

Pruning techniques[11, 13] can be applied to both the Row-Column and Vector-Radix algorithms to eliminate computation that is not necessary for the desired output points. When implemented in a distributed manner across the network of microprocessors described in Section 2, pruning the Row-Column and Vector-Radix algorithms reduces inter-node communication requirements by 50% in both cases.[6]

4. CONCLUSIONS

Our simulations show that the 2D FFT can be a useful tool in revealing the relative magnitudes of different spatial wavelengths of a signal in a material. We conclude that the pruned version of the distributed Vector-Radix 2D FFT is the most efficient of the methods investigated for rapidly assessing the health of composite materials, when the health can be inferred from low frequency components of the measured signal. Ultimately we plan to implement these algorithms experimentally. We have undertaken the initial steps needed to verify the feasibility of embedding sensors in composites, and are currently preparing a composite panel with an embedded array of micro-sensors and microprocessors.

ACKNOWLEDGMENTS

This research has been conducted at the Center of Excellence for Advanced Materials (CEAM), University of California, San Diego. Important contributions by D. Smith, Y. Huang, P. Rye, J. Aller, T. Plaisted, B. Cook, J. Isaacs and D. Lischer are acknowledged. This work has been supported in part by NSF-CMS grant number 0330450.

REFERENCES

1. S. S. Kessler, S. M. Spearing, and C. Soutis, "Damage detection in composite materials using Lamb wave methods," *Smart Mater. Struct.* **11**, pp. 269-278, 2002.
2. V. K. Varadan, and V. V. Vardin, "Microsensors, microelectromechanical systems (MEMS), and electronics for smart structures and systems," *Smart Mater. Struct.* **9**, pp. 953-972, 2000.
3. G. Zhou, and L. M. Sim, "Damage detection and assessment in fibre-reinforced composite structures with embedded fibre optic sensors - review," *Smart Mater. Struct.* **11**, pp. 925-939, 2002.
4. S. E. Watkins, G. W. Sanders, F. Akhavan, and K. Chandrashekhara, "Modal analysis using fiber optic sensors and neural networks for prediction of composite beam delamination," *Smart Mater. Struct.* **11**, pp. 489-495, 2002.
5. A. F. Starr, S. Nemat-Nasser, D. R. Smith, and D. A. Meyer, "Development of embedded microelectronic sensor networks in composite materials," *Proc. of International Workshop on Advanced Sensors, Structural Health Monitoring and Smart Structures*, pp. 1-6, Yokohama, Japan, 2003.
6. K. Loewke, D. Meyer, A. Starr, and S. Nemat-Nasser, "Structural health monitoring of composite materials using the two dimensional fast fourier transform," *Smart Mater. Struct.*, Submitted 9/13/04.
7. M. Nölle, and N. Jungclaus, "Efficient implementation of FFT-like algorithms on MIMD Systems," *Proceedings of EUSIPCO-94, 7th Eurpoean Signal Processing Conference* M. J. J. Holt et. al. (ed.), Band III, pp. 1625-1628, Edingburgh, Scotland, 1994.
8. M. Balducci, A. Choudary, and J. Hamaker, "Comparative analysis of FFT algorithms in sequential and parallel form," *Mississippi State University Conference on Digital Signal Processing*, pp. 5-16, 1996.
9. L. M. Baptist, and T. H. Cormen, "Multidimensional, multiprocessor, out-of-core FFTs with distributed memory and parallel disks," *Proceedings of the eleventh annual ACM symposium on Parallel algorithms and architectures*, pp. 242-250, Saint Malo, France, 1999.

10. W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes in C: The Art of Scientific Computing*, Cambridge University Press, 2nd Edition, pp. 504-523, 1992.
11. K. S. Knudsen, and L. T. Bruton, "Recursive pruning of the 2-D DFT with 3-D signal processing applications," *IEEE Transactions on Signal Processing* **41**, pp. 1340-1356, 1993.
12. C. Chu, "Comparison of Two-Dimensional FFT methods on the hypercube," *The Third Conference on Hypercube Concurrent Computers and Applications* **2**, pp. 1430-1437, Pasadena, California, 1989.
13. J. D. Markel, "FFT Pruning," *IEEE Transactions on Audio and Electroacoustics* **19**, pp. 305-311, 1971.