

# Genetic Algorithms-Based Parameter Optimization of a Non-Destructive Damage Detection Method

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**Abstract**—Non-destructive testing (NDT) is an important area of research, dealing with diagnostic and monitoring the health of structures and structural components and preventing catastrophic failures. One of the recently developed NDT techniques is the method of strain energy mode shapes that allows the determination of changes in structural integrity from changes in the vibrational response of a structure. Normally, application of the strain energy mode shape method requires knowing the state of a structure before it was damaged, which limits the range of the method's applicability. A modification of the strain energy method has been developed at West Virginia University. The modified (non-baseline) method does not require knowledge of the undamaged state of a structure (baseline). It has been theoretically proven that for simply supported and free-free boundary conditions the damage response can be extracted in the frequency domain by high-pass filtering. However, the filtering operation creates some distortion in the damage indicators. Some low-level damages may be "masked" by this distortion. Additionally, the theory can only predict the cut-off frequency of the filter, but cannot estimate its optimal amplitude characteristic.

In this study, genetic algorithms (GA) have been applied to produce a sufficiently optimized amplitude characteristic of a filter used to extract damage information from strain energy mode shapes. Finite element modeling has been used to produce a training data set with the known location of damages. The amplitude characteristic of the filter has been encoded as a genetic string where the pass coefficient for each harmonic of its Discrete Fourier Transform representation is a number between zero and one in 8-bit Gray code. The genetic optimization has been performed based on the minimization of the signal-to-distortion ratio. The amplitude characteristic of the filter was not limited to any specific configuration, i.e. either low- or high- pass or specific cut-off frequencies. The results obtained from the GA confirmed the theoretical predictions and allowed improvement in the method's sensitivity to damages of lower magnitude.

## I. INTRODUCTION

This paper presents an interdisciplinary research in which genetic algorithms (GA) have been used both to confirm theoretical findings and to find a near-optimal solution for a real-world problem within the framework of designing an automated damage detection system.

The original problem comes from the area of Non-Destructive Testing and Evaluation (NDTE). Methods and techniques of NDTE generally deal with detection and location in structures, machinery, etc. Early detection allows prevention of catastrophic failures that lead to economic loss and possible loss of human life. A recent project at West Virginia University had the goal of developing an automated damage detection system for Armored Vehicle Launched Bridge [1, 2]. A modal (vibration-based) method of non-destructive testing known as the Strain Energy Mode Shapes (SEMS) method was used to detect and locate damages in AVLB. Despite being a relatively new method, the strain energy method has good coverage in the research literature [3-9].

Strong features of this method include its ability to both detect and locate damage with high precision; its high sensitivity to low-level damages and relatively simple acquisition if the initial data [6]. At the same time this method suffers from its high sensitivity to measurement noise and requires knowing the original (undamaged) state of the structure before performing any tests. The latter significantly limits applicability of the method.

Consider a generic procedure involving the SEMS method (Fig. 1):

1. Vibration data are acquired on the undamaged (baseline) structure. The strain energy mode shapes are computed using the following formula:

$$U_{[a,b]} = \frac{1}{2} \int_a^b EI(\Phi'')^2 dx, \quad (1)$$

where EI is the flexural stiffness of the cross-section and  $\Phi$  is the mode shape vector (displacement mode shape). Normally, several bending modes are extracted from the structure's vibration response to be used as  $\Phi$ .

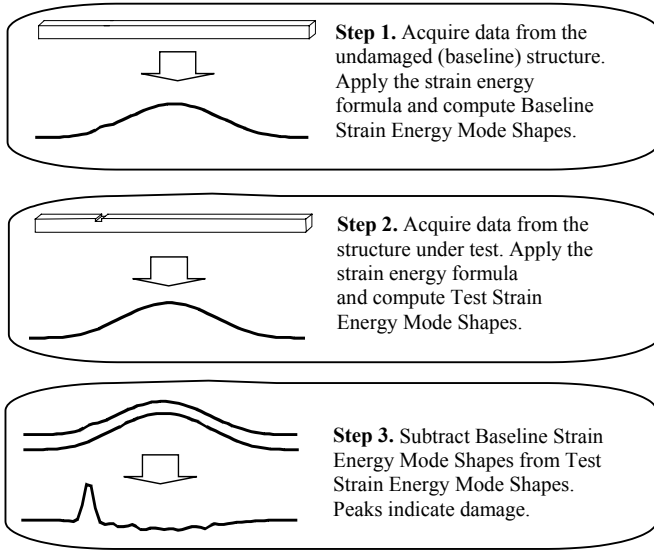


Fig. 1: Application of the strain energy mode shapes method

2. Vibration data are acquired on the structure under test. The test SEMS are computed using (1).
3. The baseline SEMS are subtracted from the test SEMS. The damage, if present, will appear as peaks on the resulting difference SEMS.

Extracting damage peaks without utilizing the baseline SEMS would significantly simplify the damage detection procedure and make the method applicable to structures without known baseline. Theoretical grounds for such a method were developed at West Virginia University [10]. The new method (called Non-Baseline SEMS method, or NBSEMS method) utilizes separation of signals in frequency domain (filtering) to extract damage peaks from the test SEMS. The new damage detection procedure is performed in the following manner:

1. Vibration data are acquired on the structure under test. Test SEMS are computed using (1).
2. Discrete Fourier Transform (DFT) is performed on the test SEMS. DFT results are converted from the complex representation to the amplitude/phase spectra representation.
3. First  $k+1$  harmonics of the amplitude spectrum (where  $k$  is the mode number: 1 for the first mode, 2 for the second, etc.) are zeroed. This is equivalent to applying an ideal high-pass filter where each harmonic has a corresponding pass coefficient that changes its amplitude but does not change its phase.
4. Inverse Discrete Fourier Transform is applied to the filtered spectra to restore the SEMS. The restored SEMS have well-expressed peaks at locations of damage.

The viability of this approach has been established theoretically and confirmed experimentally. However, the theory does not answer the question about the optimal

characteristics of the filter employed in step 3 of the procedure. The theory can only tell the minimal possible cut-off frequency that will correctly extract damage peaks.

Application of an ideal rectangular high-pass filter causes a certain amount of distortion to appear in the restored SEMS (Fig. 2). The amplitude of a damage peak depends not only on the severity of damage but also on the location, therefore this distortion degrades sensitivity of the method and creates areas where magnitude of a damage peak is less than magnitude of distortion (reduces method's coverage of the structure's length).

The goal of this research is to use genetic algorithms to experimentally determine near-optimal filter characteristics that will:

1. Confirm the theoretical findings regarding the type of the filter (high-pass) and minimal cut-off frequencies.
2. Minimize distortion in the restored SEMS and improve the method's sensitivity to damage.

## II. INITIAL DATA

A Finite Element (FE) model of a beam was used to provide data for the experiments. Parameters of the model are given in Fig. 3. Damage was modeled by removing elements; removing a single element was equivalent to inflicting 12.5% reduction in cross-section. Each displacement mode shape contained 61 points. Strain energy mode shapes were computed from the displacement mode shapes for the first five bending modes of vibration. About sixty different single damage cases and several multiple damage cases were split into the training and test data sets.

## III. PROCEDURES AND METHODS

The goal of the genetic search was to determine close to optimal characteristics of the filter used to extract damage peaks. Thus, each specimen in the population represented a filter with certain amplitude characteristic. The specimens were not programmed to take any specific configuration, i.e.

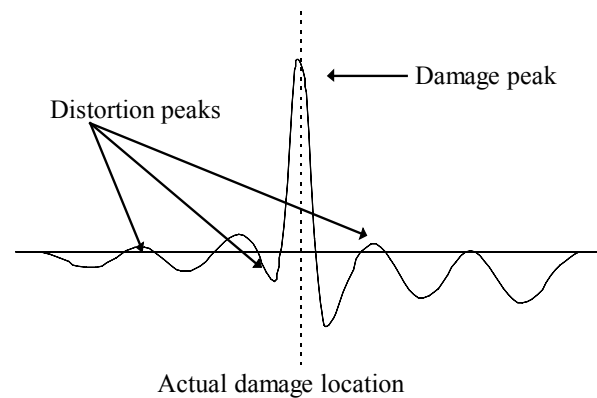


Fig. 2: Distortion caused by the high-pass filtering

Modeling software: ALGOR;  
 Element type: plate;  
 Element dimensions: 3.2 mm × 12.7 mm × 3.2 mm;  
 Number of nodes: 241 × 9.

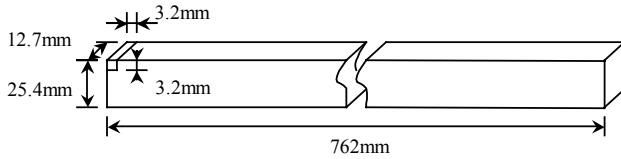


Fig. 3: FE model of a beam

high-pass, low-pass, etc. Each specimen had 31 values, determining pass coefficient for each harmonic in the spectrum. Each pass coefficient was completely independent from the others.

Two different experiments were set in order to establish how the discretization of a pass coefficient influences the results and to compare performance of the theoretically designed and genetically obtained filters. In the first experiment the pass coefficients for each harmonic were encoded by 1 bit (1-pass, 0-reject), so each specimen was 31 bit long. In the second experiment, each pass coefficient was encoded by 8-bit Gray code. This encoding provided 256 different levels between 0 and 1 that a pass coefficient could take. A specimen's length was 248 bit.

The genetic search procedure and its parameters are illustrated in Fig. 4. The GA procedure was terminated manually after improvement of the fitness function stagnated for a prolonged period of time. Generally, the GA search ran from four to eight hours on a 450 Mhz Celeron computer before being terminated.

#### IV. RESULTS

Fig. 5 shows the amplitude characteristic of a filter obtained from the population with 1 bit per pass coefficient. Fig. 6 displays the amplitude characteristic of a filter with 8-bit pass coefficient encoding. Both figures clearly indicate inhibition of the lower frequencies, suggesting a high-pass filter and thus confirming the theoretical predictions. Even for the 8-bit encoding the pass coefficients for lower frequencies are mostly reduced all the way to zero.

The differences with the theoretical prediction include higher than expected cut-off frequencies. For example, the theory calls to eliminate at least first 3 harmonics in the spectrum of SEMS of mode 1. Both genetically obtained filters remove first 7 harmonics. Apparently, the higher cut-off frequency improves signal-to-distortion ratio (defined as the ratio between the magnitude of a damage peak to the maximum magnitude of distortion).

Table I shows improvement in the damage detectability compared to the non-optimized filtering. The improvement is expressed as increase in the beam's coverage (percentage of the beam's length where a single damage can be detected).

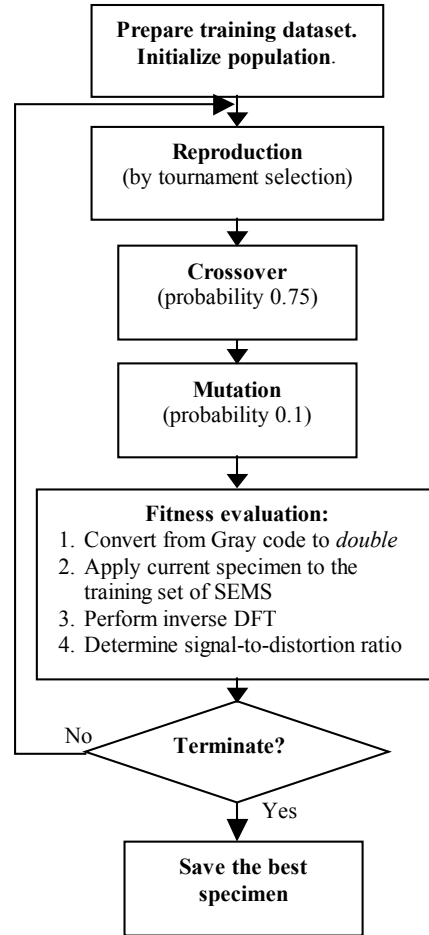


Fig. 4: Procedure for the genetic optimization

Both 1-bit and 8-bit encoded filters provided up to 16% improvement in beam coverage for any of the first five modes of vibration. There was no significant difference in the quality of improvement between the 1-bit and 8-bit encoding.

#### V. CONCLUSIONS

This paper demonstrates how methods of computational intelligence (such as genetic algorithms) can be applied both

Table I: Improvement in damage detectability

Mode#	Length covered by theoretically derived filters, % of total length	Length covered by 1-bit GA-optimized filter / improvement, % of total length	Length covered by 8-bit GA-optimized filter / improvement, % of total length
1	73.77	67.21 / -6.56	67.21 / -6.56
2	78.69	88.52 / 9.83	88.52 / 9.83
3	73.77	90.16 / 16.39	90.16 / 16.39
4	68.85	85.25 / 16.4	85.25 / 16.4
5	60.66	77.05 / 16.39	77.05 / 16.39

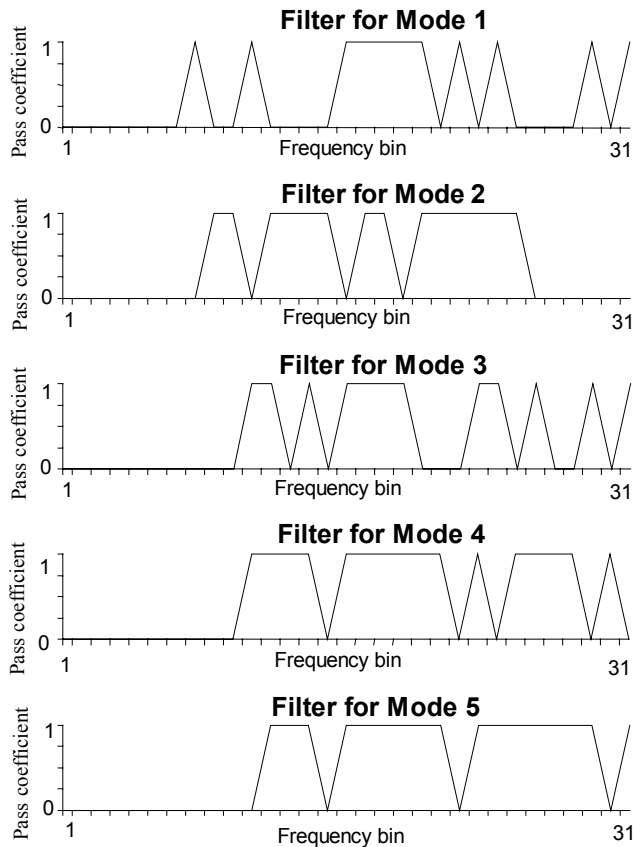


Fig. 5: Filters for the first 5 modes obtained by GA search (1-bit pass coefficient encoding)

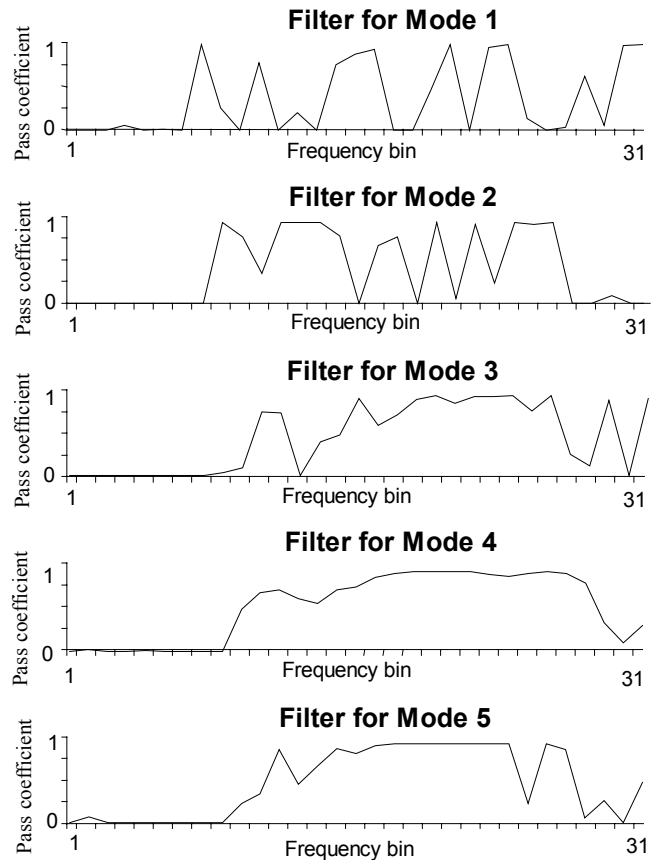


Fig. 6: Filters for the first 5 modes obtained by GA optimization (8-bit pass coefficient encoding)

to confirm a theory and improve on its practical application.

The form of the amplitude characteristic of the optimized filters provided additional proof that the suggested theory works. The achieved improvement in the signal-to-distortion ratio increased damage detectability and improved the method's sensitivity to lower-level damages, which is crucial for early detection of structural damage.

Additional benefits of such optimization come from the fact that theory behind damage detection methods usually covers simple geometric structures like beams, etc. while practical applications involve far more complex structures (in this case, Armored Vehicle Launched Bridge). The power of genetic algorithms could be used to smoothen the transition between theory and practice, and to provide a near-optimal solution for a complex problem.

## VI. ACKNOWLEDGEMENTS

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