# Damage Detection in Structural Elements Using An Immune Based Evolutionary Algorithm

S. Sahu, D. R. Parhi

**Abstract**— Damage in structural and rotating machine elements causes the local changes in the dynamical parameters of the system. Damage detection of systems represents an important research topic widely investigated. During the last two decades several researches have been conducted with reference to beams, trusses, plates, shells, bridges, offshore platforms, and other large civil structures, aerospace and composite structures to detect structural damages by monitoring the dynamic response of the system. Therefore, changes in the physical properties will cause changes in the modal properties. The aim of this chapter is to derive a simple procedure for estimating the damage in structures based on a data driven subspace identification technique. These changes in the modal parameters can be used as the input variables to find out the damage severity. The responses (natural frequencies) were obtained using finite element analysis then Clonal Selection Algorithm (a type of Artificial Immune System) is used to detect and characterize these defects. This work proposes a robust computational application of the Clonal selection theory that more accurately takes into account the affinity maturation of the immune response and produces a good converging result.

**Index Terms**— Natural frequencies, vibration, damage, clonal selection algorithm

## 1 Introduction

Damage detection of systems represents an important research topic widely investigated. During the last two decades several researches have been conducted with reference to beams, trusses, plates, shells, bridges, offshore platforms, and other large civil structures, aerospace and composite structures to detect structural damages by monitoring the dynamic response of the system. Damage in structural and rotating machine elements causes the local changes in the dynamical parameters of the system. Therefore, changes in the physical properties will cause changes in the modal properties [1,2]. The aim of this paper is to derive a simple procedure for estimating the damage in structures based on a data driven pathogen identification technique [3,4]. The changes in the modal parameters are used as the input variables to find out the damage severity. The responses (natural frequencies) were obtained using Theoretical and Finite Element analyses [5-7], and then Clonal Selection Algorithm (a type of Artificial Immune System) is used to detect and characterize these defects. This paper proposes a robust computational algorithm based on the Clonal selection theory that more accurately takes into account the affinity maturation of the immune response and produces a good converging result.

The Clonal Selection Algorithm is a type of Artificial Immune System, which describes basic features of natural immune system. The Clonal Selection Algorithm demonstrates the theory that the antibodies that can recognize the antigens are selected to proliferate, in other words they undergo replication or cloning. The selected antibodies undergo an affinity maturation process, which improves their affinity to the particular antigens.

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These antibodies normally bind to the antigens leading to their ultimate elimination by other immune cells. The proliferation used in the Clonal selection theory is a type of mitotic process; the cells divide themselves to give the required progenies, there is no crossover involved in this process. During reproduction the B-cell progenies go through an affinity maturation (hyper mutation) operation with a powerful selective pressure which results in production of antibodies with higher affinities with the particular antigen. This entire process of mutation and selection is similar to the natural selection of species. The main attribute of the immune response is that the antibodies with higher affinities are selected to become memory cells with long life period. These memory cells become eminent in future responses to this same antigen or a similar one. Figure 2 describes the of the Clonal Selection Algorithm features.

## 2 Dynamic Analysis of cracked structural element

Most structural and machine members of engineering are subjected to various loading conditions. The presence of crack changes the local stiffness. The change in the local stiffness depends on location and depth of the cracks. The changes in the dynamic responses of the structural elements have been widely used for the damage assessment. The changes in the physical properties can be used for monitoring safety, performance and structural integrity. The paper focuses on the theoretical analysis of the vibration characteristics of a bam like structural element for two end conditions.

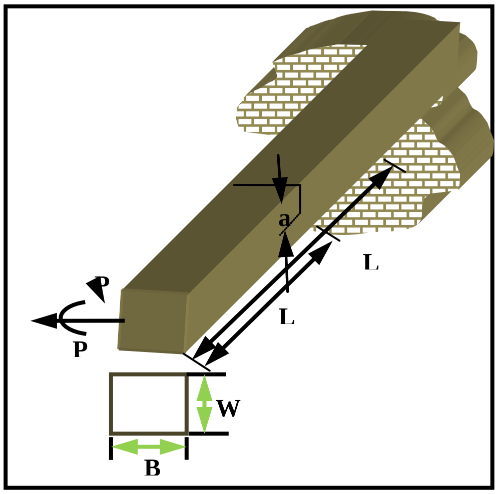


Fig 1 Geometry of the cracked cantilever beam

Due to the formation of the crack, some energy is released at the cracked section. This is known as strain energy and is a type of potential energy. The energy release rate (strain) at the cracked section is given below.

$$S_R = \frac{1}{E'}(K_{11}+K_{12})^2$$

where $\frac{1}{E'} = \frac{1-\gamma^2}{E}$ (for plain strain condition) (1a)

$= \frac{1}{E}$ (for plain stress condition) (1b)

$K_{11}$, $K_{12}$ can be defined as the stress intensity factors of mode I (opening of the crack) for load $P_1$ and $P_2$ respectively. The values of stress intensity factors from earlier studies are;

$$K_{11} = \frac{P_1}{BW}\sqrt{\pi a}\left(F_1\left(\frac{a}{W}\right)\right) \quad (2)$$

$$K_{12} = \frac{6P_2}{BW^2}\sqrt{\pi a}\left(F_2\left(\frac{a}{W}\right)\right) \quad (3)$$

Let $S_E$ be the strain energy released due to the formation of the crack. Applying Castigliano's theorem, the additional displacement along the force $P_i$ can be derived as:

$$u_i = \frac{\partial S_E}{\partial P_i} \quad (4)$$

The strain energy will take the form of

$$, S_E = \int_0^{a_1} \frac{\partial S_E}{\partial a} da = \int_0^{a_1} S_R \, da \quad (5)$$

$$S_E = \int_0^{a_1} \frac{\partial S_E}{\partial a} da = \int_0^{a_1} S_R \, da \quad (6)$$

Where $S_R = \frac{\partial S_E}{\partial a}$ the strain energy density function.

From (1) and (2), thus we have, the additional displacement can be defined as:

$$q_i = \frac{\partial}{\partial P_i}\left[\int_0^{a_1} S_R(a)\, da\right] \quad (7)$$

The co-efficient of flexibility matrix (flexibility influence co-efficient) $C_{ij}$ will be, by definition

$$C_{ij} = \frac{\partial q_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j}\int_0^{a_1} J(a)\, da \quad (8)$$

To find out all the flexibility influence co-efficient, the expression in equation (8) is integrate over the breadth.

$$C_{ij} = \frac{\partial q_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j}\int_{-B/2}^{+B/2}\int_0^{a_1} J(a)\, da\, dz \quad (9)$$

The flexibility coefficients are calculated by using the above equations to form the flexibility matrix. Taking the inverse of the flexibility matrix, the stiffness matrix is determined.

The governing equations along with the boundary conditions and normal functions yield the characteristic equation of the system as:

$$|Q| = 0 \quad (10)$$

The above determinant is a function of natural frequency (ω), the relative location of the crack (β) and the local stiffness matrix (K) which in turn is a function of the relative crack depth (a1/W).

## 3 Analysis of the cracked beam using Finite Element Method

The finite element analysis can be treated as a direct method to get the vibration parameters. The crack locations are given to the FEA method to get the changes in the natural frequencies. The finite element analysis is solved using governing differential equation of the system. The crack induction changes the stiffness of the system but the mass remains the same. The changes in the stiffness matrices have been used to obtain the natural frequencies of the system. This method of calculating the natural frequencies have been adapted by the finite element method software ALGOR package. To identify the crack presence and to help in the generation of the data base ALGOR (Version 19) has been used to evaluate the vibration parameters of cracked and uncracked beam. First the beam element with different single crack is plotted using CATIA V5R15 software, and then they are treated in ALGOR environment. The uncracked and cracked beam model is then analyzed in ALGOR environment. First of all the mesh generation is performed. The mesh size is around 1.4529mm and approximately 33369 elements are created. Then the parameters such as element type (brick and isotropic), material name (Aluminium Alloy) are defined in the ALGOR environment. The model unit is then changed to S.I. standards. Then in the 'analysis window', the particular analysis type is selected (natural frequency i.e. modal analysis). Then the analysis is performed and the first three modes of natural frequencies at different crack locations and crack depths of the cantilever and fixed-fixed beam are recorded. The length and cross-sectional area of the beam are 800 mm, and 38 X 6 mm2, respectively. As per the material properties the modulus of elasticity (E) is 70,000 Mpa, the density (ρ) is 2700 kg/m3. In the finite element analysis of the cracked cantilever beam having V-shaped single crack is taken into account.

## 4 Analysis of Clonal Selection algorithm

The clonal selection algorithm is a one type of Artificial Immune System, which describes basic features of natural immune system. The clonal selection algorithm demonstrates the theory that the antibodies that can recognize the antigens are selected to proliferate, in other words they undergo replication or cloning. The selected antibodies undergo an affinity maturation process, which improves their affinity to the particular antigens. The Clonal selection theory (CST) explains the reaction to an antigenic inducement in an adaptable immune system. Generally, it is assumed in Clonal selection algorithm that if the antibody recognizes an antigen with a certain affinity then it is selected for cloning to produce antibodies in high volumes. These antibodies normally bind to the antigens leading to their ultimate elimination by other immune cells. The proliferation used in the Clonal selection theory is a type of mitotic process; the cells divide themselves to give the required progenies, there is no crossover involved in this process [8-10]. During reproduction the B-cell progenies go through a affinity maturation (hyper mutation) operation with a powerful selective pressure which results in production of antibodies with higher affinities with the particular antigen. This entire process of mutation and selection is similar to the natural selection of species. The main attribute of the immune response is that the antibodies with higher affinities are selected to become memory cells with long life period [11,12]. These memory cells are illustrious in future responses to this same antigen or a similar one. Figure 2 describes the of the clonal selection algorithm features.

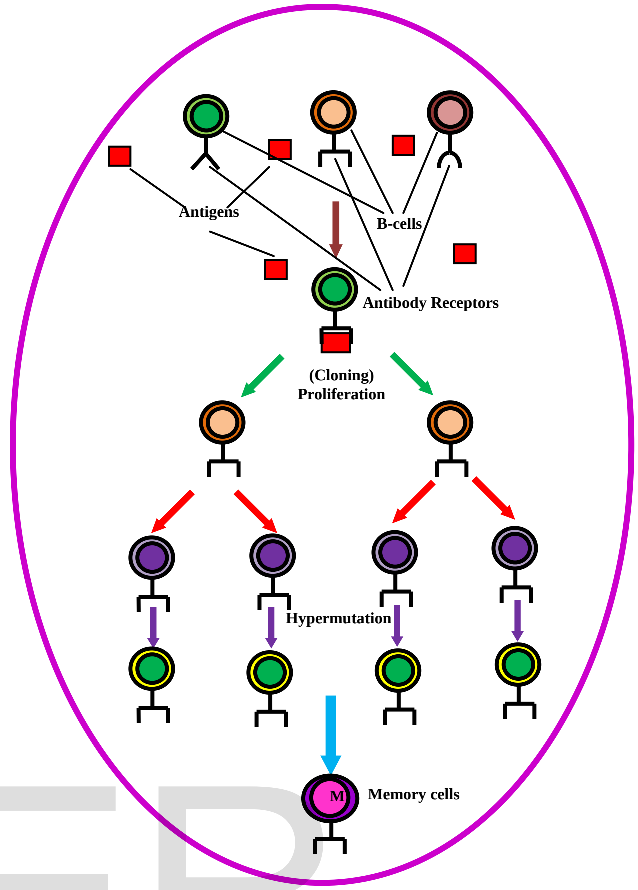


Fig 2 Pictorial representation of clonal selection algorithm



## 5 Result Tables

((FEA result – result from the proposed technique) / (FEA result)) × 100 (11)

((Exp. result – result from the proposed technique) / (Exp. result)) × 100 (12)

Total error in %= (% error in rcd + % error in rcl)/2 (13)

TABLE 1
Relative Natural Frequencies from FEA

| Sl. No | rfnf from FEA | rsnf from FEA | rtnf from FEA | rcd from FEA | rcl from FEA |
|---|---|---|---|---|---|
| 1 | 0.992 | 0.991 | 0.996 | 0.325 | 0.218 |
| 2 | 0.993 | 0.992 | 0.997 | 0.3 | 0.206 |
| 3 | 0.994 | 0.994 | 0.997 | 0.287 | 0.231 |
| 4 | 0.995 | 0.997 | 0.999 | 0.125 | 0.218 |
| 5 | 0.997 | 0.997 | 0.996 | 0.275 | 0.362 |

TABLE 2

| Sl. No | rcd using the CSA technique | rcl using the CSA technique | percentage error rcd | percentage error rcl | Total error |
|---|---|---|---|---|---|
| 1 | 0.315 | 0.212 | 2.95 | 2.87 | 2.91 |
| 2 | 0.291 | 0.200 | 2.99 | 2.92 | 2.95 |
| 3 | 0.278 | 0.223 | 3.12 | 3.18 | 3.15 |
| 4 | 0.121 | 0.212 | 2.88 | 2.88 | 2.88 |
| 5 | 0.266 | 0.351 | 3.08 | 3.1 | 3.09 |

Comparison of results from CSA with FEA

## 5 Conclusions

This work describes an inverse method to predict the damage location (rcd, rcl) using a soft computing method. The proposed soft computing method is a type of Artificial Immune System (AIS) known as Clonal Selection Algorithm (CSA), which used to design and develop the algorithm. Then the natural frequencies are (treated as inputs) trained in the algorithm to predict the crack location which forms the inverse method. The results give the direct comparison of the results with the Finite Element Analysis (FEA) and Experimental Analysis. The results found to be in good agreement with the results of the FEA and Experimental Analysis. The errors are found to be within 3%. The errors are found out using the equations 11-13.

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