STRUCTURAL DEFECT DETECTOR BASED ON VERY LOW POWER, LOW COST, LESS COMPLEXITY, AND WIRELESS COMMUNICATION METHOD

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Abstract— The aim of this work is to develop a wireless low power, low cost acquisition device to communicate and analyze the data which is accumulated from remote structural defects or using this technique for wireless remote monitoring system. The main challenge is to achieve the goal with minimum power consumption, low cost, less complexity and easy to maintain which have been discussed with regards the collecting process of data over a period of times as well as the power consumption rate. In this research a smart PZT sensors that can be used as sensors and actuators to build adaptive and health monitoring aerospace structures associated with two XBee's of their built in microcontroller and signal generator IC chip to develop a structural defect detector or a monitoring system. Analyzing and monitoring program have been written in MATLAB to read the received serial data directly from the XBee port, and this data have been collected directly by one remote XBee that is attached with the structural body near to couple attached PZT sensors and energized with low capacity battery directly without using extra components, the results show obvious different, in received sensors data, between the two plats under test, one of them has a mechanical defect which is punched with a hole of 4mm diameter size.

Index Terms— Low power Wireless Communication, MATLAB, Piezoelectric material (PZT), Structural Defect Detector methods, XBee module, ZigBee.

I. INTRODUCTION

The very cruel flight environment which is due to the large changes in pressure, humidity, temperature, speed, and all other loading conditions, that are consequently cause a lot of stress to the aircraft structure and frame. Accordingly, corrosion, cracks, disbands, delaminating, and other failures sneak when the aircraft is in service time. Traditionally, inspection methods which require planned interference and periodic detection as well as, in some cases the dissociation of some parts, results in high costs incurred because of its necessity.
Piezoelectric materials are a category of smart materials, which can be used as sensors and actuators to build adaptive and health monitoring aerospace structures.

A.Structural Health Monitoring
During the life of a structure, Structural Health Monitoring (SHM) provides at every moment a diagnosis of the "state" of the full assembly of these parts constituting the structure as a whole, and of the basic materials of the different parts. The structure state must remain in the field which specified in the design, even though this can be changed by normal aging due to usage, by the environment and accidental events. With the help of Usage Monitoring, it can provide a prediction, evolution of damage, residual life, etc.. SHM involves the integration of sensors, data transmission, probably smart materials, computational power, and handing out ability inside the structures. It makes it possible to reconsider the design and the full management of the structure [1]. This is schematically presented in Fig. 1.

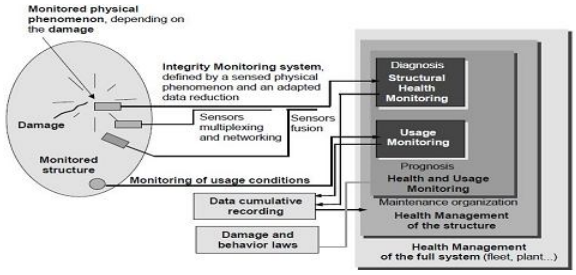

Fig. 1, Principle and organization of a SHM system

A. *Wireless sensor networks*

The implementation of wireless sensor networks is well known in the above application because of low-power circuit design, simple, reasonably efficient wireless communication equipment and improved small-scale energy supplies have combined with reduced manufacturing costs. ZigBee, XBee is a specification for a matching set of high level communication protocols based on an IEEE 802 standard for personal area networks. XBee devices are often used in mesh form to transmit data over longer distances, passing data through middle devices to reach more distant ones. This allows XBee networks to be created ad-hoc, with no high-power control transmitter/ receiver, able to reach all of the devices. The Network can cover a range of 10- 100 meters. The size of a XBee is compared with that of a 1 coin in Fig. 2.

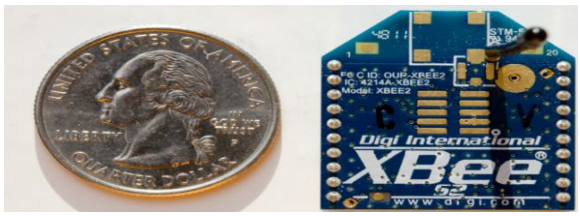

Fig. 2, XBee size

B. Objectives:

The objectives of project are as follow:

1. To develop a wireless communication tool with very low power, low cost and less components acquisition device to communicate and analyze the data framework, which will take advantage of recent advances in a number of related areas such as: Piezoelectric, Electromechanical Equivalent Circuit, Piezoelectric Sensors and wireless communication nodes modeling.
2. To utilize the capabilities of the XBee construction and its embedded microcontroller to serve data process and acquisition of Piezoelectric in both cases as a sensors and actuator.
3. To tailor the functionality of this framework so that it is suitable for low power consumption, and wireless communication for remote structural defects exploration and monitoring system.
4. To deploy this method in various studies and fields for developing in application of remote structural defects exploration and monitoring system.

II. LITERATURE REVIEW

C. Damage Detection Methods

Rytter in 1993 proposed a categorization system for SHM damage identification method [2] (Rytter and Kirkegaard 1994). Originally, this categorization system, included 4 levels, is expanded by Inman [3] (Inman 2003), who added 3, levels later. These levels of categorization can be reflected the structural modern health monitoring. The reviewed levels of this categorization system are in following:

1. Notice the damage existence
2. Notice the damage existence and location
3. Notice the damage location and quantification
4. The remaining life notification, location, quantification and prediction (Prognosis).
5. Combination of Level four with the smart structure in order to form a self-evaluating system
6. Combination of Level four with the smart structure in order to form a self-healing system
7. Combination with control activation in order to form health monitoring and control simultaneously

Pearis (2002) incorporated successfully the levels 1 and 6 of Rytter-Inman's categorization system [4] (Peairs 2002). This research involved the loose bolt detection with a SMA (shape memory alloy) actuator in order to return the original torque to the bolted joint.

Though Pearis' experiment is not coupled with an independent system, his study was an attempting lead to begin removing shortcomings in the categorization system and between industry and research.

The frequency of resonant shift technique is perhaps the maximum instinctive vibration technique used to notice the structural damage.

When m is the mass and k is the stiffness, the natural frequency of elementary vibrations for a single degree of freedom system, is:

Usually, the aim of this method is detecting a change in difficulty of the structure, meanwhile the mass is supposed constant. Such a change in frequency will effect on FRF (frequency response function) as the resonant frequency is decreased. This method can detect a global change in the structure and can be categorized as one of the 3 methods of simple modal parameter. The two other modal parameter approaches are changing in modal damping and modal shapes [5] (Doebling, Farrar et al. 1996). Salawu (1997) express in literature that, the terms natural frequency, model frequency and resonant frequency are stating to the similar item. Though Salawu's paper in 1997 is not only for presenting the mathematical background of resonant frequency changes, but a very good explanation for reviewing of damage diagnostics with using changes of resonant frequency. Moreover, only resonant frequency change and shifts in type shapes will be discoursed in current literature review. The most important disadvantage of the resonant frequency shift system is the little sensitivity of damaging, which needs great levels of damage or very exact measurements [6] (Doebling, Farrar et al. 1998). In contrast, the resonant frequency system displays less statistic difference of random error bases, rather than the other modal parameter techniques [5,7] (Doebling, Farrar et al. 1996, Farrar, Doebling et al. 1997).

D. Wireless sensors-based structural health monitoring

Many SHM approaches have been offered in the previous decades; though, experiments have to be overwhelmed earlier than can be functioned to the structures of civil engineering. Most current SHM procedures need straight input excitation measurement for implementation. In many cases, however, there is not any easy way for measuring the inputs or external exciting of the structure alternatively. These difficulties have limited the usage of current SHM approaches which necessitate the input excitations' measurements. Method which founded on ambient vibration has become more significant in the case of damage detection and SHM. Further research efforts could be directed to the SHM development methodologies which reduce the necessity of measuring the input excitation and handle the cases of ambient vibration. The other challenge consequences from this fact are that structures' damage is a local phenomenon intrinsically. Sensors which are close to a damaged site are predicted to be rather deeply influenced than the ones which are far to it. Consequently, to notice damage effectively in a structure at the arbitrary locations, sensors have to be distributed densely in the structure. Maximum existing SHM approaches accept the measured data are centrally to be acquired. Traditionally usage of wired sensors to imply this SHM system with a compressed sensors array is absolutely challenging since the existence of difficulties in maintaining and deploying the related wiring plant. Obviously, the wiring system for the

huge civil infrastructures is too complicated and so problematic to manage. Furthermore, fabulous amount of data are expectedly generated that would requisite to be referred to the central station. Managing this enormous amount of data is challenging too and not to be cost-effective. Hence, damage notification of enormous civil organization of traditional employing wired sensors is inflexible. Last developments of smart sensors have made usage of SHM a compact array of possible sensors. The necessary feature of the smart sensors is the on-board micro-processor, which provides for the sensors the 'smart' features. Programming can be surrounded in the sensor micro-processor, which let the smart sensors to locally save data, perform the favorite computations, scan valued information, make 'if–then' decision, send outcomes fast, etc. Consequently, for damage detection a portion of calculation can be completed at the level of local sensor. Inessential information can be rejected, in order to reduce the information which necessities to be moved back to the central station. Notice that all the smart sensors are wireless to date as well, founded on RF (radio frequency) communications with data transmission. Algorithms of damage detection that can take the distributed computing environment advantage presented by technology of the smart sensor are extremely desired, but limited currently. Compressed arrangement of smart low-cost wireless sensors has potentially improved the SHM quality and dramatically used the wireless communication and on-board computational capabilities. This wireless sensor offers worth information that SHM algorithms can utilize to locate, detect and assess structural damage produced by severe loading events and by environmental progressive deterioration as well as the SHM system economical realization. Information from compactly instrumented structures is expected to effect in deeper insight to the structural system's physical state.

Cho et al. [8] (Cho, Yun et al. 2008) show the outcomes of cooperative international research on the smart wireless sensor and civil structures' SHM amongst Korean Science and Technology Institute, University of Illinois at Urbana-Champaign and the University of Michigan. They argue the state of the art in the wireless smart sensor technology and the sub-systems of the wireless smart sensor and wireless available sensor platforms established in the industry and academia are reviewed. Three wireless smart SHM systems established by the writers and applied to different SHM civil structures' types have been presented. The first system is a modal distributed identification one which using a wireless smart sensor platform, that is useful in a historic theatre to the balcony structure's model identification. The second system is an autonomous, wireless and low-cost tension estimation one for cable-stayed bridges that is hired for tension estimation and modal identification of a stay cable. The third and last one is a decentralized independent SHM system that is used to damage recognition on a 3-D steel truss structure. Different available wireless smart sensor platforms are illustrated in Fig. 3.



Fig. 3, Various available wireless sensor platforms.

Lee et al. [9] reveal the health-monitoring process for under ordinary bridges traffic loadings (Lee, Kim et al. 2002). A process for bridge structure's damage estimation is accessible using vibration ambient data produced by the loadings of traffic. The process contains the identification of the operational modal possessions and damage assessment's severities and locations. A process is existing for the element-level bridge damage assessment with using the modal possessions attained from the vibration information produced by normal traffic loadings and confirmed by a sequences of vehicle experiments on the bridge model. It has been proved that major amount of the imposed damages can be successfully noticed for different vehicle load situations; though, generally the damage degree of severity inclines to be a little bit overestimated. For applied applications, the precision of the probable damage severities is less significant, lengthy the damage positions can be noticed accurately.

Rice and Spencer carried out the SHM sensor development for the Imote2 platform [10] (Rice and Spencer Jr 2008). They have discovered that the improvement of a adaptable Imote2 sensor-board with on-board signal processing designed specifically for the SHM demands applications. The components of the accelero-meter board have been selected carefully to let for the high-resolution and low-noise data acquirement which is necessary to successful algorithms of implement SHM. The testing and design of a lately developed SHM-A (Structural Health Monitoring Accelerometer) board which interfaces with the wireless Imote2 sensor platform is offered and verified experimentally.

Lynch et al. [11] approved the validation of a wireless modular monitoring system for structures (Lynch, Law et al. 2002). The wireless sensing components for using in a WiMMS (Wireless Modular Monitoring System) have been planned and made. Sketching on the technological advanced developments in the wireless areas communications, MEMS sensing transducers and low-power micro-processors, the wireless sensor component signifies a high-performance but still low-cost resolution to monitor the long-term and short-term structural performances. The novel employing conception of computational core for the sensing of wireless component for local data cross-examination organizations has been examined. A FFT (Fast Fourier Transform) has been implemented successfully and the initial response modes of a structure locally identified by a sensing of wireless component attached on a experiment structure.

E. Damage detection techniques

Kessler et al. approved studies on damage recognition in combination materials applying Lamb waves [12] (Kessler, Spearing et al. 2002). This paper shows part of an analytical and experimental survey of approaches for in situ damage recognition of compound materials. Experimental consequences are revealed for the Lamb wave procedures application to quasi-isotropic epoxy/ graphite experiment specimens comprising symbolic damage modes, containing transverse, defamed limitation layer through-holes and cracks. Park et al. present the modal flexibility-based damage detection technique of steel beam by dynamic strain measurements using FBG sensors [13] (Park, Koo et al. 2007). It has been proved that the strain-flexibility method applying dynamic straining measurements of FBG sensors can successfully notice and focus manifold little damages close to the sensors. The bridge damage location was identified applying PNNs. Firstly; modal parameters were recognized from the ambient vibration data and were exploited as the feature directions for PNNs. The consequences gained from field experiments briefing is as follows: (1) PNN presented worthy estimation consequences in noticing single damage position. (2) PNN applying progressive estimation organization is utilized successfully to notice manifold damages. (3) The conventional BPNNs (Back-Propagation Neural Networks) can be another way to notice manifold damages. (4) It is easy to imply PNN and it is rather effective for compound constructions than conservative neural networks.

III. METHODOLOGY

F. Hardware

Fig. 4, shows the overall low power wireless multi-sensor SHM system that we developed for defect detection and assessment in a structure integrity monitoring. It embeds the ultrasonic Pieozo-sensor and data acquisition electronics into the structure by using XBee RF Modules capabilities and radios for node communication and control. The PIC 155 has been chosen as transmitter and receiver sensor for the reason of its categorized under soft piezo-ceramic. Defects detection, categorization and localization are prepared in three stages: node stage (sensing), Generation/ acquisition Processing stage, wireless communication stage and base-stage (Analyzing). The sensing nodes are responsible for sine wave signal generation and signal collection, while the Generation/ acquisition Processing stage manage and control the sensing nodes, and the wireless communication stage relay sensor data to the base station. Within each set of sensors, cluster, when the sensing node is exciting test sine wave in the structure, all the other wireless nodes are waiting to respond. The received signal of the surrounded sensor nodes of any defect would be altered by blocking the signal path or cause wave spreading. A Laptop PC is the base station with a one XBee RF Module receiver. The diagnosis process of the defect has been done by using a comparison between the generated and the listened signal that we will present in the next section. It is seen that with this wireless network, and data acquisitions were performed in a distributed and combined manner. This structural design also permits the fully coverage of aircraft structures to be examined and allows sensing nodes to combine detect defect marks, reduce power consumption, and false alarms.

The main components of the system which is used can be described as the following sub-subjects:-

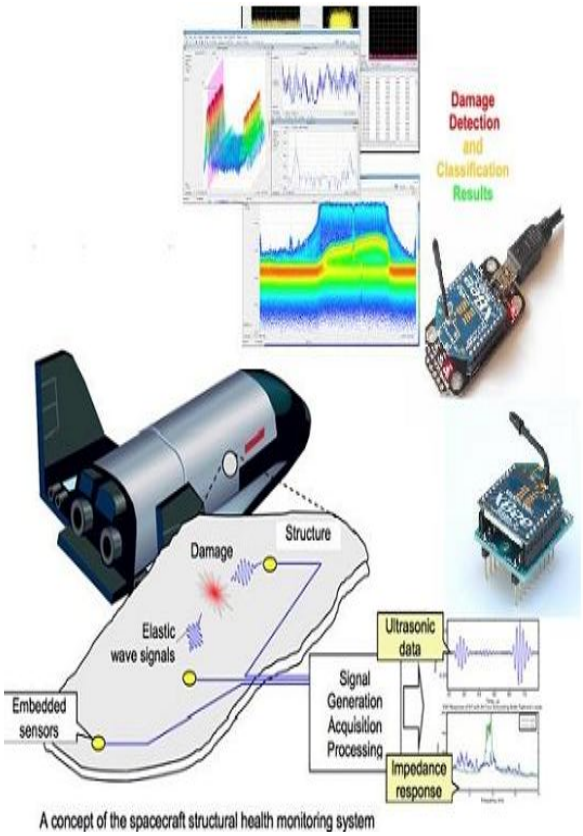

Fig. 4, Shows the overall low power wireless multi-sensor SHM system.

G. Sine wave Generator for piezo actuator excitation

Fig. 5, shows design and prototype of the sin wave board for piezo actuator excitation. It is based on the standard operation amplifier 741, with output 3Vp-p and 1.5 offset. It can generate a frequency tune able from 100 Hz to 1.5 kHz. The power consumption of this circuit is less than 20 mW for 0.3% duty cycle. A typical signal generator output signal is shown in Fig. 5, where a flexibility of frequency change could be done through the XBee or settled manually. It is tested that this circuit can be used for PIC 155 PZT disk sensors over the same range of frequency and it can effectively produce vibration signal with 3V amplitude.

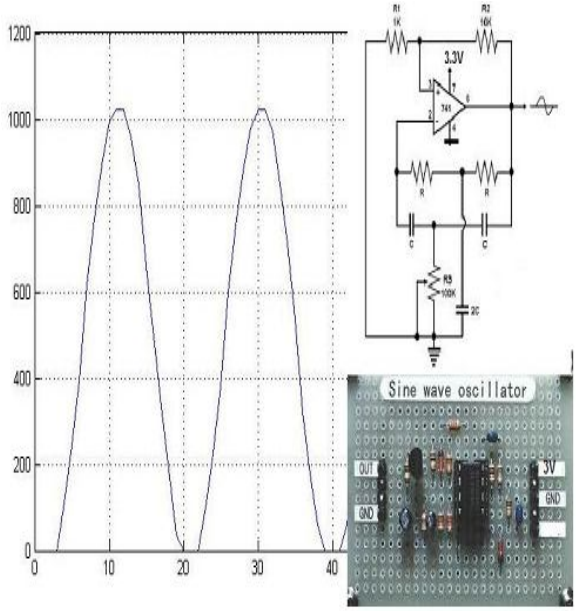

Fig. 5, Sine wave Generator for piezo actuator excitation.

H. Wireless RF Modules Node Hardware

In this research, we used the property of XBee to processing and wireless radio communications of the analogue data. XBee technology is a low-cost, low-power wireless sensor networks. The modules require minimal power and provide reliable delivery of data between devices. The modules operate within the ISM 2.4 GHz frequency band. The benefits of XBee technology are: secure, low cost, reliable, very long battery life, and can be used worldwide.

XBee radios have multiple I/O lines that can be used to collect digital or analog data, and then transmit that data to another XBee for interpretation.

I. Generate Sample Data and properly interpret the results.

The analogue to digital converter (ADC) on XBee radios are 10-bit, which will provide a resolution from 0 to 1023 (0x03FF hex). Each XBee has varying requirements for acceptable ADC voltage ranges. The selected XBee supplied with not exceed 3.3V on any pin to avoid the damage the radio module. The secondary microcontroller on this XBee is connected to the ADC pins instead of the RF processor, as we can see in Fig. 6.

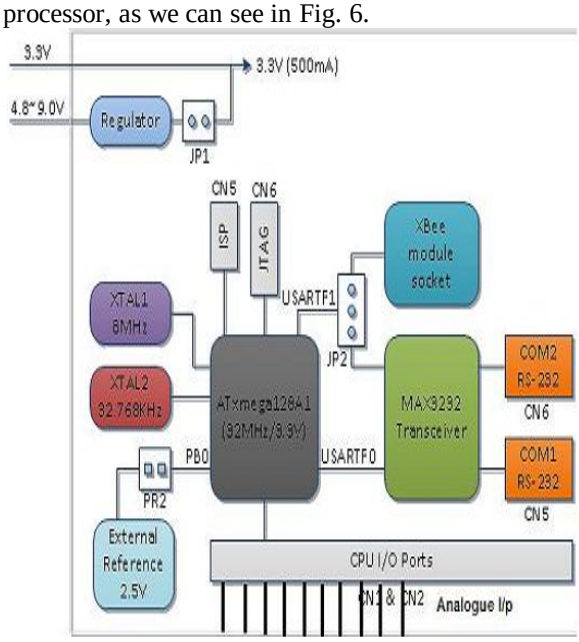

Fig. 6, Block Diagram of the XBee

J. Experimental Results

The data acquisition portion of the SHM method involves several components, such as, selecting the excitation methods, number and locations, sensors type, and the data processing that includes acquisition, storage, and data transmitting/ receiving hardware. The economic considerations will play a major role in the field of making to take the decisions of system elements selection as well as, data intervals at which be collected which is another consideration that must be considered.

Referring to Fig. 4, there were only two types of components that have been used in this research the PIC 155 PZT Sensors, and two XBee's, as a data acquisition circuit and as a wireless communication node.

The process of analyzing and choosing data to pass on or reject from the feature selection process, is subjected to the algorithm of the program that we are used to process the received data. As an example, an inspection of the experiment setup may tell that a sensor was insecurely mounted, so based on the decision of the individual sensors data that performing the measurement, this set of data of particular sensor may be selected to be deleted from the quality selection process. Signal processing procedures like re-sampling and filtering can also be considered as data cleansing methods.

Since communicate wirelessly and remotely with very low power consumption and less complexity to the inspector is the objective and motivation of this work. Refereing to Fig. 7, we will list a several steps to describe the procedure:-

- Setting up the PIC 155 PZT Sensor

Two PZT sensors, PIC 155, are placed on the variety bout 12 cm as a displacement between transmitter/ actuator sensor and the receiver sensor on an

aluminum plate. The measurements have been implemented on the experiment test conducted with two conditions.

- Reference specimen plate with no defect.
- Punched specimen with a defect of about 4mm hole size.

F. Wireless Communication Node Configuration

There are two methods to sample data in XBee: Automatic sampling. In which, the radio takes a sample either periodically (based on a sample rate) or when a change is detected on one or more digital pins. This will sample the XBee's I/O lines and transmit that sample to another XBee that could specify with the Destination Address parameters. With Automatic sampling, one radio requests the sample data from another XBee using a Remote AT Command. The radio will periodically sample all of the I/O lines that are set as inputs of the sensors and send the sample data to a destination XBee, connected with PC. We selected the maximum sample rate that could be set.

By using the XCTU program, we configured the two XBees as per Fig. 8, where the transmitter XBee node functions as follows:-

- Control the Sine wave generator circuit, which is connected to the PZT actuator sensor to supply a signal with optional frequency and limited by 3 V battery biasing voltage.
- Read directly a received vibrated signal from four PZT sensors and convert them to digital with its imbedded 10 bits analogue to digital converter, then transfer these data though its radio circuit to the reciever one.

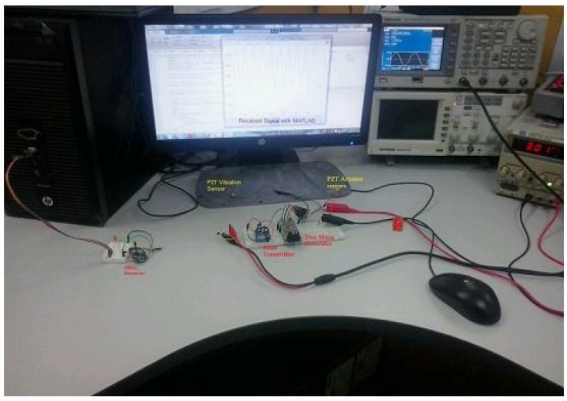

Fig. 7, SHM Practical measurements test.

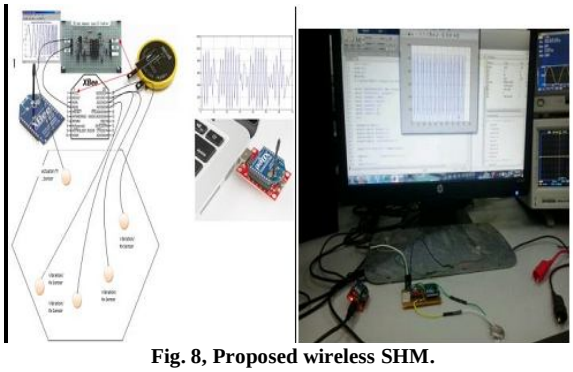

Fig. 8, Proposed wireless SHM.

The other XBee operated as a receiver for the transmitted serial data coming from the Transmitter XBee, the last XBee is controlled by a software driver written in MATLAB.

IV. RESULTS AND DISCUSSION

Referring to Fig. 7, the Matalb direct communicate with the receiver XBee to read the attained serial data frame, the program algorithm is used to access the data, recognize the analogue channels data from the received frame bytes, decoding the data, analyzing, and drawing the results, this process is performed for two cases, defected and non defected plate.

The drawing of the results are shown in Fig. 9,10. and Fig. 9, respectively.

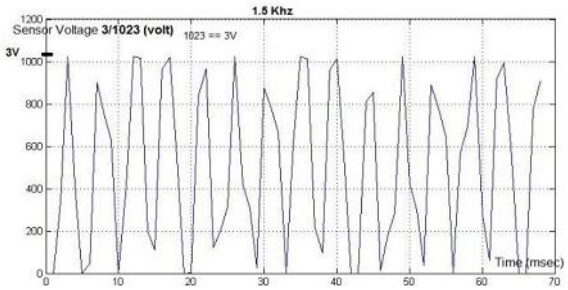

Fig. 9, Represents No defect plate, 1.5 KHz received signal by PZT sensor.

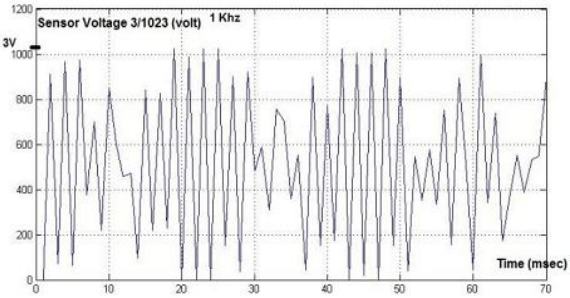

Fig. 10, Represents No defect plate, 1 KHz received signal by PZT sensor.

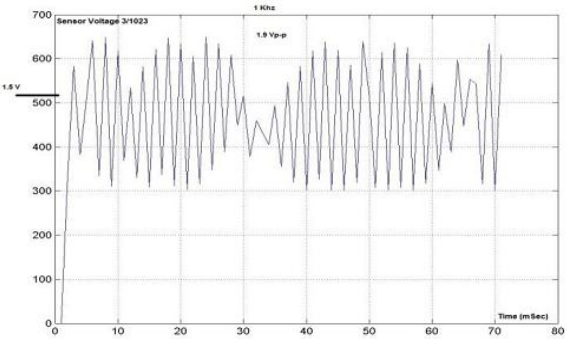

Fig. 11, Represents Defected plate, 1 KHz received signal by PZT sensor.

Fig. 9 and 10, shows a significant results of two investigated cases , we have found that, there is no distortion or attenuation in the sensor output voltage signal and consequently, the received data is similar to the PZT actuator send data, this results prove that

the same signal have been received under no defect or damage specimen material, the output signal amplitude value is 3V, which is equivalent to 1023 decimal code because the 10-bit ACD of the XBee, while the results of Fig. 11, shows a significant variation in amplitude due the defection of punching specimen. The interpretation based on that the excited sine wave signal which is propagate by the PZT actuator throughout the material structure, this signal has influenced by the damage of specimen and has distorted, amplitude attenuation proportional with the position of the PZT sensor with respect to the defection. It is foud that the signal which is traveled between the PZT actuator and the sensors has a value of 1.9Vp.p, the sensors supposed to be distributed to cover particular area on the body to be able defecting detection at any point.

A. Advantages

- *Minimum power consumption, low cost, less complexity and easy to maintain which have been discussed with regards the collecting process of data over a period of times.*
- Bi-directional wireless communication thanks to XBee modules.
- Each XBee unit has a unique serial number. This means two (or more) units can be set up to exclusively talk to each other, ignoring all signals from other modules. This is not easily achieved with other modules.
- The XBee module has in build 'data-packet' building and error-checking to ensure reliable data transmission.
- Due to this minimum energy small single battery with 3 volt can be energize the transmission set of circuit and can be charged with small size solar cells.

B. Disadvantages

- Relatively Low data rate (250 kbit/s) which Limits frequency maximum sampling time.
- It should maintain the communication with the remote XBee as long as the measurements are required.

CONCLUSION AND FUTURE WORK

This work used the capabilities of the ZegBee, XBee module to achieve all the required objectives of the SHM inspection test, such as low power consumption rate, less complexity of components, warless serial communication, direct data process and drawing.

It is worth mentioned that this direct coupling between the transmitter XBee from one side and the signal generator and PZT sensors from another side, as seen in Fig. 7 and 8, this direct matching would be sufficient for less than 5 sensors, otherwise multiplexer circuit should be added to cover more sensors if needed, new configuration setting by using the available digital input/ output pins of XBee to control the multiplexer addresses.

The novelty of this method is not only the for more energy saving but also less in components, because this method hadn't use additional microcontroller to process or manage the data or XBees, consequently the resolution is higher than past due to less conversion time when processing the data.

A. Future Works

Although this thesis has advanced the state of the art in the wireless modular components and energy saving of SHM systems, further work is necessary in order to be integrated into aircraft, this includes the following:

- Robustness testing of the punched plate with regards to the reduced sampling rates and frequencies that could be attained with high speed wireless systems.
- Further reduction in the power rate requirements of wireless transducer systems when low power relatively high voltage signal required.
- Damage detection search over a particular geometric distribution on aircraft structures using this proposed techniques.

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