Stand Alone Smart Bolt for e-Maintenance

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***Abstract*—The present paper introduces a new configuration of a smart bolt capable of sensing the variation of its axial tension. The information is processed in a built-in board and a wireless alarm is sent to a receiver to inform about the health of the bolts at any time. Both way communications is allowed within a designed network of bolts in a plant. For the sake of less cumbrousness, the whole board is space optimized with battery less trials.**

***Index Terms*—Tension monitoring, smart bolt, condition based monitoring, wireless.**

I. Introduction

The maintenance of machinery and industrial plants constitutes a huge cost to industry. Structures such as buildings, bridges, pipelines, petroleum plants, ships and aircraft must be robustly designed and regularly inspected to prevent 'wear and tear' damage from causing catastrophic failures. Inspection is expensive and time consuming, while designing to prevent damage can compromise performance. Analyzing the tension of the bolt is key inspection factor in construction safety. Hence most known methods are based on the monitoring of the tension. Precision of bolt tightening is one of the major issues noted in plants as to whether accurate preload is achieved or not. Insufficient preload, caused by an inaccurate tightening method, is a frequent cause of bolted joint failure which may lead to potentially catastrophic structural failures. The loss of tension may occur due to vibration, thermal effects, change in the material characteristics…etc. It is important for the designer to appreciate the features and characteristics of the main methods employed to tighten bolts. Presented below is a brief summary of the major bolt tightening methods. However, whatever method is used to tighten a bolt, a degree of bolt preload scatter is to be expected [1].

The recent advances related to bolted joints have seen a tremendous development to ease inspection of the fastening tension. For visual inspection, the smart bolt [2] is a bolt with a color changing indicator in the head. It is based upon the response of an optical micro-indicator element to the deflection of one internal portion of a fastener relative to another as the fastener elongates under tensile loading. This transforms into reproducible color change. The Maxbolt from [3] has a cartridge with needle embedded in the bolt to indicate variations of stress. Other inventions in a couple of patents [4] have needle in washers, hence when it loses the needle changes direction. For wired inspection, bolt with electric termination is to be connected to a wire for instant measurements of preload, service load and overload of bolted assemblies. This includes Standard Internally Gaged Hex Head Cap Screws or the SPC4 load indicating fastener from [5]. The boltMike [6] based on ultrasonic inspection of bolts, determines the length of a fastener by measuring how it takes for sound to travel its length before, after tightening or during inspection period.

Manuscript received June 28, 2012; revised Septmber 1, 2012. This work was supported by King Abdulaziz City for Science and Technology (KACST) through King Fahd University of Petroleum and Minerals (KFUPM) on the project No-09ELE75804 as part of NSTP.

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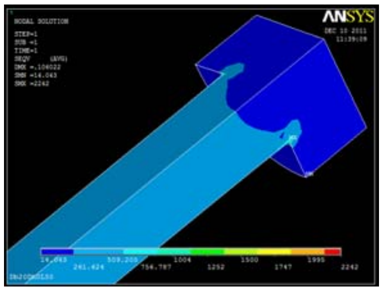
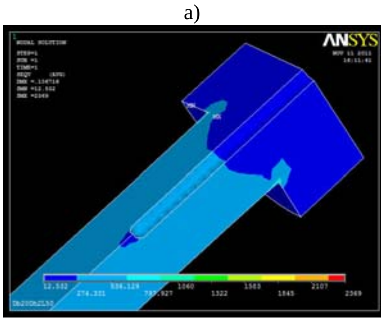
II. Considered Design Aspects

A. Smart Bolt Design

There are various ways to monitor the stress in a tightened bolt and many have already been patented [2]-[13] or filed by the authors [14], [15]. Two groups of possible techniques for stress measurements encompass either the bolt itself needing extra manufacturing, or, component added to the washer for tension monitoring e.g. piezoelectric washer. In this application a gauge was inserted in the bolt body as shown in Fig. 1. The effect of drilling a hole does not affect the material strength at all. Fig. 2 and Fig. 3 show Von Mises stress distribution and axial elongation for both bolts without and with drilled hole using the following data: L=50 mm, hole 2 mm over 20 mm. Material Steel E= 200 GPA η =0.3, allowable stress 80-100 MPa. Finite element analysis in Fig. 1 has shown that adding a small hole of 2 mm diameter over a length of 20 mm does not affect the bolt strength integrity.



a)



b)

Fig. 1. Von Mises stress distribution (a) without hole and (b) with added hole to the bolt.

B. Bolt Stress Monitoring

There are three ways to monitor a variation of a stress in a bolted joint; longitudinal elongation of the bolt, deformation of the washer under preload, color, and radial deformation of the whole. In this paper, the axial tension of the bolt was monitored by measuring the stress over the length of the bolt. A whole of 2mm diameter has been drilled and a foil strain gage has been inserted. The gage resistance is about 120 Ohm, uniaxial, with leads at the top. It uses polyester-coated copper 2-wire cable. The operating temperature range is -55 to 150^{o}C. The voltage is obtained from the strain gage bridge and is given by:

$$V_o = \frac{E}{4} K_s \cdot \varepsilon_o \tag{1}$$

where E is the bridge voltage, K_s is the gage factor (e.g.2), and ε_o is the strain output.

Hence, the strain output is proportional to the bridge voltage by the factor $4 / EK_s$. Assuming $K_s = 2$, Fig. 2 shows variation of the strain output depending on the supplied voltage. As the supplied voltage remains small, the strain output increases. It is important to maintain the voltage supplied to the strain constant otherwise precision of reading the current tension will be lost. If the battery drain over time is known, a compensation could be applied. A calibrated torque meter with USB link to a PC was used to calibrate the strain gage. Hence, within the program, data reading could either be made for current torque applied or related axial tension currently applied to the bolt. Any variation of the bolt tightness will be noticed by the gage and hence information is sent to the micro controller for post processing.

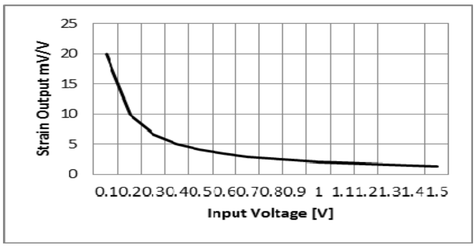


Fig. 2. Output of strain gauge.

Since an alarm will be sent to inform about any variation of the bolt tension after the bolt is tighten. A threshold value has to be determined based on the sensitivity of the signal conditioning board used to amplify the signal. Two instrumentation amplifiers were tested i.e. LTC 6800 and LM 358. The first one was selected based on its stability and high gain.

Fig. 3 shows the behavior of the signal acquired when the bolt was going through various status e.g. loose, increase tightening and full tightening. The torque was varying up to 130 Nm corresponding to a voltage of 1.03 V approximately. An Atmel based microcontroller used was designed to acquire data, to process them, to send a wireless alarm, and, to get back to sleep mode. The objective was to ensure minimum power consumption in all system including wireless network of many bolts.

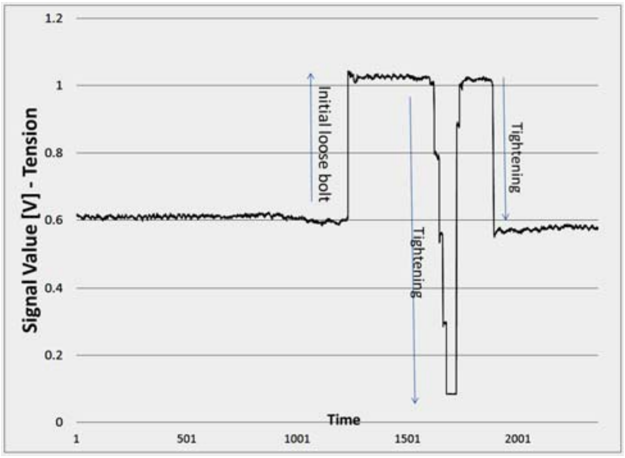


Fig. 3. Measured bolt tension.

III. Energy Consumption

NS-2 was used to evaluate the energy consumption of packet transmission for randomly deployed sensor nodes assuming two popular routing protocols: LEACH [16] and LEACH-C [17]. The operation of each protocol is briefly summarized next.

A. LEACH Protocol

Because LEACH (Low-Energy Adaptive Clustering Hierarchy) is a clustering-based protocol that utilizes randomized rotation of local cluster based station (cluster-heads) to evenly distribute the energy load among the sensors in the network. LEACH is distributed and uses localized coordination to enable scalability and robustness for dynamic networks [16].

TABLE I: Several AA Battery Brands With Their Capacity Characteristics [18]

	Zinc–carbon	Alkaline	Li-FeS2	NiCd	NiMH	NiZn
Capacity under 500mA constant drain [mAh]	400-1000	1800-2600	2700-3400	600–1000	2200–2900	1500-1800
Nominal Voltage	1.5	1.5	1.5	1.25	1.25	1.65
Rechargeable	No	No	No	Yes	Yes	Yes
Joule	5400	14040	18360	4500	13050	10692

Using the specific capacity characteristics presented in TABLE , the following Table II shows the lifetime for the network under LEACH routing protocol for different batteries while Table III shows the lifetime for the network under LEACH-C.

TABLE II: Network Lifetime (Hours) for Type of AA Batteries for LEACH

#nodes	Zinc–carbon	Alkaline	Li-FeS2[3]	NiCd	NiMH	NiZn
50	4.13	10.75	14.05	3.44	10.00	8.18
100	3.60	9.40	12.23	3.00	8.70	7.13
150	1.45	3.67	4.80	1.18	3.41	2.80
200	0.75	1.94	2.54	0.62	1.81	1.48
250	0.49	1.19	1.56	0.38	1.11	0.91

TABLE III: NETWORK LIFETIME (HOURS) FOR TYPE OF AA BATTERIES FOR LEACH-C

#nodes	Zinc–carbon	Alkaline	Li-FeS2	NiCd	NiMH	NiZn
50	8.54	22.20	29.03	7.12	20.63	16.91
100	3.63	9.44	12.34	3.02	8.77	7.19
150	2.58	6.71	8.78	2.15	6.23	5.11
200	1.83	4.75	6.21	1.52	2.00	3.62
250	1.51	3.92	5.12	1.26	3.64	2.99

B. LEACH-Centralized Protocol

As described above LEACH is an adaptive protocol, but it has no guarantee about the placement and/or number of cluster head nodes. LEACH-C [17] is a central control algorithm to form the clusters. The base station plays the role of cluster formation. Therefore, during the set-up phase of LEACH-C, each node sends information about its current location and energy level to the BS. In addition, the BS ensures even an energy distribution among all the nodes. And it uses the simulated annealing algorithm to solve the NP-hard problem of finding optimal clusters. Once the cluster heads and associated clusters are found, the BS broadcasts a message that contains this information.

As recommend by [16], the number of cluster heads is 5% of the total sensor nodes in the network. In the beginning of the simulation, each sensor node is equipped with a battery of 5 joule. The metric of packet per joule shows the cost of each packet in terms of joule. It is computed by dividing the total number of data packets received by the base station by the total energy consumed during the simulation period (500 seconds) including the base station. Each point in the graph is an average of 10 random topologies performance. It is assumed that each node transmits one packet every TDMA cycle and the cycles are contagious (i.e. data transmission does not stop for the whole simulation period). Each cluster head sends one aggregated packet that summarizes the information received from all its children. For example, there is a need of 3.9 mJ when 50 nodes are deployed to deliver one packet at the base station based on Leach (Fig. 4).

IV. CONCLUSION

A design and make of a standalone smart bolt was presented in this paper. The first initial tests show that the approach taken to design this smart bolt is very promising. The tension is assessed through calibration of the output signal that may reach 150 Nm in torque usually used for major ranges of bolts. This will be used for e-maintenance and would guarantee later a great safety for plants and mechanical structures. Further work is in progress to manage hundreds of bolts in a network and treat false alarms.

ACKNOWLEDGMENT

The authors would like to acknowledge the support provided by King Abdulaziz City for Science and Technology (KACST) through King Fahd University of Petroleum & Minerals (KFUPM) for funding this project No.09ELE75804 as part of the National Science, Technology and Innovation Plan.

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