Design of Embedded Wireless Sensor and its Soft Encapsulation for Embedded Monitoring of Helicopter Planetary Gear Set

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Abstract. Planetary gear set, as an important part of helicopter, is with the characteristics of multi-point and time-varying position engagement. For the revolution of planetary gears round sun gear, directions of vibration and pulse created by tooth damage change continuously. If an accelerometer fixed on the surface of gearbox, the angle between the directions of pulse force and accelerometer sensitivity will change continuously, which will causes that the components of pulse force on the sensitivity direction vary with time and the features of damage are very difficult to extract from the signals. Aiming at this problem, a type of embedded wireless sensor node was designed firstly, which can be fixed on the carrier of planetary gear, and acquires the damage-related vibration signals in a fixed direction of pulse force. Then, to avoid the corrosion of electronic components by the lubrication oil in gearbox, the protect restrictions of the sensor node was investigated and a kind of soft encapsulation method is applied. Finally, real vibration signal is measured and transmitted by the designed and/or encapsulated sensor node. The experiments show that the sensor can measure vibration effectively.

1. Introduction
Transmission system, constructed by shafts, vertical gears, bevel gears, planetary gear set, bearings, etc, is one of the most complex subsystems of helicopter. Especially, the planetary gear set is with the characteristics of multi-point and time-varying position engagement. For the revolution of planetary gears round the sun gear, the directions of vibration and pulse created by tooth damage change continuously. If an accelerometer fixed on surface of the main gearbox, the angle between the directions of pulse force and accelerometer sensitivity will also change continuously. As a complex modulation problem, it causes that the components of pulse force on the sensitivity direction vary with time and the features of damage are very difficult to extract from the signals. So how to acquire the signals responding the conditions is a key problem in fault detection and diagnosis of planetary gear set. Wireless sensor nodes, embedded on the planetary gear carrier and rotating with planetary gear’s revolution round the sun gear, are hopeful to acquire the vibration signal stably at fixed directions of pulse force, and eliminate the effect created by engagement position varying. Through the increasing of SNR (Signal to Noise Ratio) of damage feature, the complex modulation problem is hopeful to be resolved from the source of signal acquisition.

In recent years, many researchers have studied on this problem. In 1996 and 1998, Jammu and Wang, et al. investigated how to select the vibration sensors for monitoring the main transmitter in
OH-58A helicopters [1]. In 2000, Holm-Hansen et al. analyzed the effect of embedded sensor installation to bearing’s mechanical strength by finite component analysis [2]. In 2002, to resolve the embedded sensing problem of helicopter transmitter, Danai et al. analyzed the demands and constraints of main transmitter monitoring for OH-58D helicopter, and selected the mode and frequency of wireless signal transmission. Baldwin et al. gave a method based on Bragg fibre optic sensors for the monitoring of transmission ring gears in 2007 [3]. In 2008, Coker et al. separated the vibration signal from seeded faults in rotorcraft transmissions through fibre optic strain sensors [4]. In 2010, Wang et al. introduced a generic sensor network design framework based on a detectability measure for test optimization in PHM (Prognosis and Health Management) [5]. Based on physical models, Cheng et al. selected the features for monitoring and gave an approach for detect damage quantitatively of planetary gear sets [6, 7]. Although it has been well-considered in monitoring the health of helicopter transmitter by the sensors fixed on the gearbox surface, such as accelerometer, etc, the signals gotten from such approach are easy to be disturbed by noise and the features of early fault are difficult to be extracted because they do not acquired so directly.

To measure vibration and transmit the data wirelessly, many researches have been done. A type of wireless accelerometer node called G-link was produced by Microstrain Ltd., and applied in the research of CBM (Condition based Maintenance) by Tiwari et al. in 2001 [8]. Beetech, a company in China, also developed a series of wireless accelerometer in recent years [9], etc.

The study and application of embedded wireless sensor node and/or network have developed a new approach for distributable data acquisition, damage estimation and rapid expansion of health monitoring system. But in real engineering, the package and protection of wireless sensor node, especially in mal-conditions, are still key problems needed to be considered. Most of the wireless sensors, no matter in the market or in research, are all packaged and protected by the shell and send signals through an interior or external antenna. Their shells, no matter make by metal or metalloid, can be called hard package and all need to be designed and machined by mechanical engineers. There are lots of constraints in their application, such as topography not easy to control, sealing ability not enough, etc.

In this paper, to acquire and send the vibration signal of helicopter planetary gear set, a type of wireless sensor node is designed firstly. Several of these nodes can automatically construct a wireless sensor network, measure vibration signals in real time, and increase SNR by its installation near the damage. For the circumstance is very adverse in helicopter main gearbox, a new type of soft encapsulation method is investigated based on disphenol A epoxy resin mixed with amine hardener to protect the embedded vibration sensor node for planetary gear set monitoring. The experiments and performance analysis show that the sensor node and its encapsulation is suitable for the need of engineering.

2. Design of embedded wireless vibration sensor

2.1. Model of wireless sensor networks for planetary gear set

According to the structures of helicopter transmission chain, an experimental system with two classes of planetary gear sets was build, in which the first class planetary gear set is constructed by one sun gear and four planetary gears. To monitor the health of all gears, four wireless sensor nodes were proposed to be installed and each one is embedded in the space between two adjacent gears, as shown in figure 1. To form an embedded wireless sensor network, the sensor nodes send data continuously, an external receiver (can be also called sink node) receives the data through the antenna extends into the gear box, and a signal processing device is applied to analyze the received vibration data.

2.2. Hardware of embedded wireless vibration sensor node

There are three aspects included in the hardware design of embedded wireless vibration sensor node. First, an adaptive sensor satisfied the demands for vibration signal measurement need to be selected. Second, aiming at the needs of vibration signal acquisition, processing and data transmission, a
suitable processor should be selected and the special antenna need to be designed to achieve the ability of signal processing and communication. Third, an effective node package method needs to be designed to meet the constraints and requirements of node installation in gearbox, and achieve the maximum efficiency of signal transmitting.

There are lots of RF chips applied to the near-field communication for data processing and communication, among which CC2430, an integrated chip from Chipcon, is highly integrated and with less peripheral chips. To design the sensor node as small as possible, CC2430 is chosen as the core processor of the sensor node. Considering CC2430 can get 250kbps data rate in transmission, if there is no collision in media access and no resend because of distortion, all data is sampled on real time and saved with 16bit long, the highest frequency for sampling and transmitting in real time can be calculated as 3.5kHz. To measure mechanical vibration signal at an embed way, a low-power 3-axis linear accelerometer LIS3L02AL was selected as the vibration sensor, which has a full scale of ±2g and a bandwidth of 1.5 kHz for three axes. After the integrating of accelerometer, conditioning circuit, core processor, on board antenna, and rechargeable lithium battery, as shown in figure 2, a complete wireless vibration sensor node can be designed and manufactured.

3. Soft encapsulation of wireless sensor node

3.1. Packaging constraints and common methods comparison
Although vibration signals from the gear damage can be effectively detected by the wireless sensor nodes embedded on planetary gear carrier in helicopter, the protect requirements are very strict because of the sensor nodes are fixed in the gearbox and turn with planetary gear all the time. The constraints of sensor installation and protection can be included as:

- Strict seal. As planetary gear set makes use of the lubrication with splash, the whole or part sensors installed on the planetary gear carrier are inevitably immersed in the lubricating oil when the planetary gear rotates. If the sensor seal is not strict enough, the oil leaking into the shell will corrosive affects the electronic components, PCB (Printed Circuit Board), etc., and greatly shortens the life of sensor nodes.
- Sufficient strength and mechanical properties. To ensure sufficient rigidity and distortion-free transmission of vibration signals, sensor nodes are often required to install by the means of preload before used. In addition, the collision may arise inevitably in the process of use and transport. Therefore, the shell of sensor nodes must have sufficient strength and good mechanical properties to improve safety.
• Easy fabrication. The internal space of planetary gear box is very small, sensor nodes may need to be made into complex shapes. Considering the PCB of sensor node only needs to cut on the surface, which made it easy to create complex shapes for actual needs, the encapsulation materials of sensor node should also be easy to fabricate into complex shapes.

• Good electromagnetic compatibility. To reduce the size of embedded wireless sensor node, interior antennas are often designed for communication. In packaging, the antenna must be covered by encapsulation material, which requires the materials having no effect on wireless communication or as small as possible.

Aiming at the above requirements, the performances of several encapsulation materials commonly used, such as polycarbonate, steel, aluminium, ceramic, etc, are compared. It can be known that the strength of steel, aluminium and ceramics is very high, but their fabrication of complex shapes is difficult, and it is difficult to achieve strict seal. The electromagnetic shielding of steel and aluminium is strong, while polycarbonate is not well when immersed in oil. Therefore, these materials are all difficult to meet all the above constraints for embedding sensor node in planetary gear set.

3.2. Soft encapsulation method based on disphenol A epoxy resin mixed with amine hardener

Soft encapsulation is a packaging method that the hard shell needs not to be installed in protection of circuit board, but all of the chips, wires, and joints are covered by some soft encapsulation material to achieve the purpose of circuit protection.

Epoxy resin is a typical soft encapsulation material. In traditionally, the heat-curing process of epoxy resin encapsulating a circuit board needs a long time. In 2009, Liu et al. carried on the research on disphenol A epoxy resin mixed with amine hardener (HUNTSMAN1564/3486 series). The result of their research shows that this type of material series has the following characteristics [10]:

• The materials have very good liquidity and binding property before curing.
• Curing conditions are very good. The best curing temperature is 60°C, at which the curing time is about 4 hours (curing degree is over 90%). It can be also cured properly after 60 hours in the natural temperature (15 °C to 25 °C), and the curing shrinkage rate is 1% -2%.
• Mechanical property is very good after curing. The tensile strength of cured material is 65.2Mpa. The flexural strength is 95.1Mpa. The Rockwell hardness is HRC55. The material is stable and easy to machine after curing. It has good property for protecting of oil/water immersion and acid corrosion.
• The material has low density after curing.

Therefore, the property of disphenol A epoxy resin mixed with amine hardener is very good, which has good prospect to be used as soft encapsulation material.

3.3. Procedure of soft encapsulation

As disphenol A epoxy resin and amine hardener are both liquid before curing, they can be used for whole-liquid non-based soft encapsulation. Its procedure can be represented as the following steps.

• Step1: Designing and manufacturing an encapsulation mould according to the shape, size, installation space constraints and the packaging need of sensor nodes.
• Step2: Putting the sensor and its assembling parts into the mould, and adjusting their height to make the PCB of sensor parallel with the bottom of mould.
• Step3: Mixing disphenol A epoxy resin with amine hardener at the mass ratio of 3:1.
• Step4: Pouring the mixed liquid material slowly into the mould, and then place it into curing chamber at 60 °C for 4 hours, or at natural temperature for 60 hours.
• Step5: Taking out of the encapsulated sensor node, and processing its surface.
4. Experiments and analysis

4.1. Test of wireless communication

RSSI (Receive Signal Strength Indication) is measured at different distances between sensor node and sink node. For CC2430 has a function for power detection, it can send out the voltage value of the battery for power supply. After averaging of the experiment data, the results of RSSI can be obtained at different power supply voltage as well as at different distances, as shown in table 1. From this table, it can be seen that the designed sensor node can communicate with sink node in 20 meters.

| Distance | Voltage | 0m | 5m | 10m | 15m | 20m |
|----------|---------|----|----|-----|-----|-----|
|          | 2.4V    | -19| -70| -76 | -80 | -82 |
|          | 2.8V    | -18| -62| -68 | -78 | -80 |
|          | 3.2V    | -17| -61| -67 | -70 | -79 |
|          | 3.6V    | -16| -62| -66 | -72 | -79 |

4.2. Vibration measurement experiment

For the core processor, CC2430, has only 128kB flash memory and must be first applied for storage of all the software, such Zigbee stack, sampling code, etc, statistics suggest that only 900 samples of data can be saved continuously in the chip. If the sampling frequency was selected as 1kHz, which means the maximum frequency of the signal must be lower than 400Hz, the resolution rate will be about 1.1Hz.

Figure 3 is the original time-domain signal waveform measured by a sensor node under the conditions that acceleration amplitude is 1g, and the frequency is 80Hz. Figure 4 is the spectrum corresponding to the signal in figure 3. From figure 3 and figure 4, it can be seen that although some harmonic components are given by spectral analysis, the measurement results reflect the actual vibration signal. The harmonic components may be caused by the low stiffness of clamp.

4.3. Performance verification of node encapsulation

4.3.1. Oil immersion test. To assess whether oil may leak into the shell and whether the node can communicate normally in the oil, an encapsulated sensor node was completely immersed in the gear oil for 10 days. After the long-term completely soak of sensor node by the oil, it can be known that there is no oil leakage in the shell, and the immersed sensor node can send and receive signals properly.
4.3.2. Signal transmission experiment. The RSSI value of the soft encapsulated node and the non-encapsulated node with power supplies of about 3.2V are shown in table 2. It can be seen that the shell have small effect on communication, and RSSI declined slightly, which means this encapsulation method can be used in real engineering.

| Sensor type     | Distance | 0m | 5m | 10m | 15m | 20m |
|-----------------|----------|----|----|-----|-----|-----|
| Non-encapsulated|          | -17| -61| -67 | -70 | -79 |
| Encapsulated    |          | -18| -62| -69 | -71 | -81 |

5. Conclusion
Aiming at the monitoring requirements for helicopter planetary gear set, a new type of embedded wireless vibration sensor node was designed in this paper. After the selection of encapsulation materials, a new soft encapsulation method based on disphenol A epoxy resin mixed with amine hardener is proposed. Through the verification experiments of wireless communication, vibration measurement, and protection, the following conclusions can be drawn:

- The vibration sensor node can acquire the vibration signal, which indicates a promising future on embedded fault detection of the helicopter planetary gear set.
- The materials of the soft encapsulation method are both liquid, which enable the shell to be formed in full accordance with the mould shape and completely fit the surface of electronic components and PCB. After the solidification, the materials enjoy the feature of high cured strength, high stiffness, and good insulation.

Acknowledgments
The authors awfully thank the financial supported by National Natural Science Foundation of China under Grant No.50975279 and No. 50905183.

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