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LOW MAINTENANCE MEMS PACKAGING FOR ROTOR BLADE INTEGRATION

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ABSTRACT
Rotor blade integrated MEMS pressure sensors can be used for detecting and quantifying BVI on helicopter blades. The sensor package we present here is predestined for this application because it protects sensitive measurement parts from harsh environmental conditions. Maintenance effort and time can be reduced in case of sensor malfunction due to its two-component package, consisting of sensor carrier and a capsule which can be easily replaced.

INTRODUCTION
Lift forces of helicopters are produced by rotating rotor blades as they generate downward directed airstreams. In horizontal flight, this airstream and its turbulences is pushed downwards away from the blade plane. But if the helicopter is descending, it follows the lift airstream and finally hits these turbulences with its own blades (Figure 1).

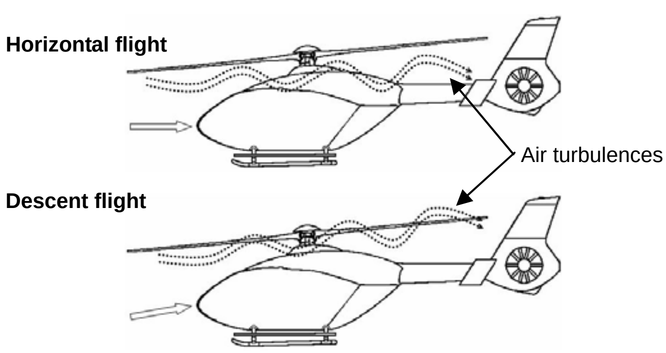

Figure 1. Helicopter blade-vortex interaction during descent flight situation.

This interaction is called "Blade-Vortex Interaction" (BVI) and causes impulsive low-frequent noise levels that can be recognized on ground even far away. If these BVI situations are detected [1], they can be controlled by servo-flaps located at the trailing edge on the outer regions of a rotor blade. The flaps generate compensating tip pressure amplitudes which minimize BVI induced turbulences [2]. Present BVI detection techniques can be divided into two main categories: Direct measurement of aerodynamic effects like pressure fluctuations and indirect measurement of BVI induced and emitted noise either in near or far field. In past, microphones have been used in far-field noise detection experiments. They have been mounted under the rotor blade both on helicopter frame and outside of it. Best results were obtained from microphones outside of the helicopter but this position is practically not applicable in real flight.
PVDF foils mounted directly on the rotor blade were used for structure-born noise measurements. But there are several unwanted noise sources inside and outside the rotor blade which interfere with the BVI noise signal and even by extensive signal processing it was not possible to reliably detect BVI occurrence.

BVI directly results in pressure fluctuations on the rotor blade which can be measured by surface-mounted MEMS pressure sensors. The sensor's sensitivity depends on its position on the rotor blade and decreases by increasing distances away from the leading edge. The best position is around the leading edge. In previous works, commercial pressure sensors have been arranged on a rotor blade for BVI detection under real flight testing but they have been destroyed rapidly in the harsh helicopter environment.

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HARSH HELICOPTER ENVIRONMENT

Impacting particles like hail, sand corns or water drops are the main problem for surface integrated pressure sensors. For instance, piezoresistive pressure sensors consist of thin silicon membranes with thicknesses in the order of several micrometers and therefore will be quickly destroyed by high speed impinging particles. Also erosion effects and material abrasion negatively affect the sensor's sensitivity.

The angled rotational movement of the rotor blade produces acceleration forces of different magnitudes (see Figure 2). There is a 1000 g static outward load in the radial direction and in the downward direction normal to the rotor blade plane there is 100 g static acceleration superposed by 10 g transient load caused by vibrational movement.

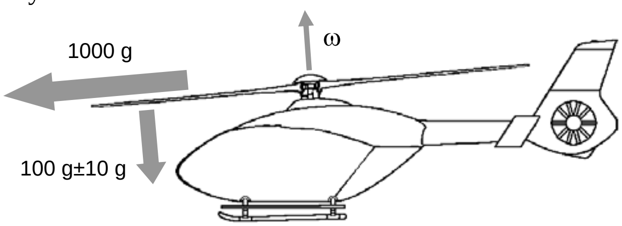

Figure 2. Force components of rotating helicopter blade.

TWO-COMPONENT MEMS PACKAGE CONCEPT

Extreme rotor blade conditions require a robust MEMS sensor package that is applicable for helicopter blade integration. On the one hand BVI pressure has to be sensed precisely. This is best done with piezoresistive sensors. We use an absolute pressure sensing silicon chip with a maximum pressure load capability of 2.5 bar. The piezoresistive elements and electrical connections are hermetically sealed on the lower side of the chip. On the other hand the sensor' membrane is fragile and has to withstand particle impact. These two facts lead to a lid-protected sensor enclosure in which the sensor chip is protected and the membrane can not be hit by particles directly. In this concept, pressure changes are transmitted in the inner volume through tiny lid-holes with diameters of 200 µm. Through these holes not only air but also dirt particles can intrude and cover the sensor chip while moisture and water may affect electrical connections and result in material corrosion. These effects can not be avoided completely and as a result the sensor has to be eventually replaced sometimes even if some semi-permeable membrane would be used in the sensor lid. To simplify the replacement process we developed a two-component pressure sensor package which consists of a carrier (grey colored part in Figure 3) and a sensor capsule (yellow colored) [3].

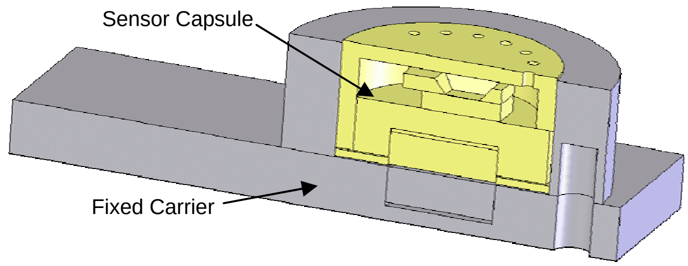

Figure 3. Robust two-component MEMS sensor package.

The carrier is permanently integrated in the rotor blade and contains electrical connections for sensor signal transmission and power. The capsule is mounted exchangeably inside the carrier frame and acts as a housing for the pressure sensor chip.

Mechanical Mount

Because the carrier is integrated fixed in the rotor blade it has to be constructed robust, that is why screws, pins or clamping systems as mechanical connections between capsule and carrier are explicitly avoided. Instead, the mechanical joint is done by two small cylindrical permanent magnets made of NdFeB with a diameter of 3 mm and a height of 1 mm. One magnet is mounted on the carrier while the other is fixed inside the capsule. Therefore the capsule can be easily swapped and installed inside the carrier while the magnetic force will fix it. We measured the force between two opposite magnets to be 1.25 N. The only force that may cause the capsule to fly away from the rotor blade is the vibration induced load in normal direction to the blade plane of 10 g as illustrated in Figure 2. The capsule's mass of 0.35 gram multiplied by the mentioned 10 g maximum vertical dynamic acceleration leads to a resulting force of 0.034 N which is very small compared to the magnetic force of 1.25 N between two magnets. As a result, the magnets are powerful enough to ensure mechanical mounting and to withstand dynamic vibration conditions in the rotor blade.

Electrical Connection

The electrical connection between capsule and carrier is realized by an electrically anisotropic conductive elastomere. As can be seen in Figure 4a from top view, the electrical anisotropy results from gold plated brass wires with diameters of around 30 µm which are vertically embedded into a silicone elastomere with pitches of 30 – 50 µm. The wires are isolated between each other through the silicone substrate with an insulation resistance of 1.0×10^9 Ω. The contact resistance between upper and lower side of foil decreases with increasing compression load, e.g. from 100 mΩ at 1 N/mm^2 to 50 mΩ at 4 N/mm^2.

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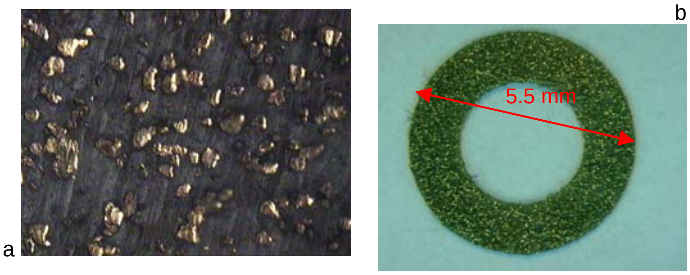

Figure 4. a) Top-view of electrical anisotropic elastic foil. b) Cut circular foil ring.

The foil has two tasks, one is to establish the electrical connection between capsule and carrier and the second is to be a sealing unit against moisture because of its elasticity. To find out the elasticity curve we tested a sample of foil (see Figure 4b) in a compression test facility. The sample cut out is shaped as a circular ring with inner and outer diameters of 3.1 mm and 5.5 mm respectively. The foil's thickness is 200 µm. The resulting elasticity curve is shown in Figure 5.

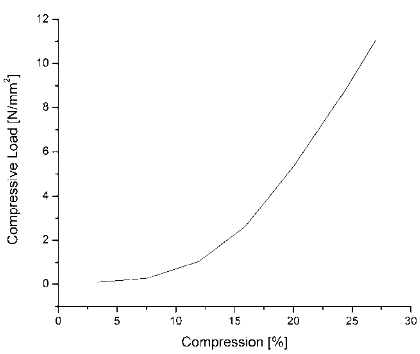

Figure 5. Elasticity curve of the anisotropic elastic foil.

In the two-component package, the required force to compress the foil will be applied by two permanent magnets. Their force is 1.25 N which is distributed over a foil area of 16.2 mm^2 leading to a compression load of $7.7x10^{-2}$ N/mm^2 which is sufficient for maintaining electrical connection and establishing a sealing compression.

PROTOTYPE SENSOR

A prototype sensor based on the two-component package was fabricated and assembled. A cross-sectional schematic view of the prototype sensor is shown in Figure 6. The FR4 PCB substrate is blue, the steel grey while the permanent magnets and elastic foil are marked yellow and green respectively.

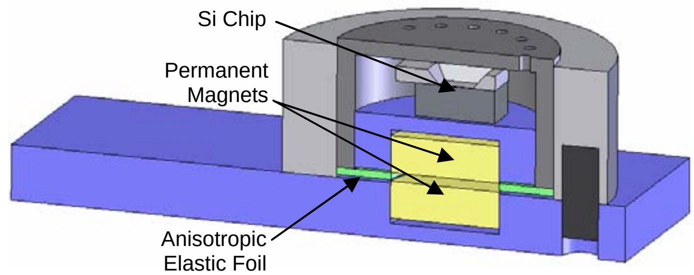

Figure 6. Cross-sectional view of the packaging concept.

Sensor Capsule

The PCB board is the fundamental carrier for the silicon pressure sensor chip. All electrical parts and bonds of the chip are located on its lower side away from the medium to be measured. Conventional bonding techniques require the bond pads to be adjacent in one plane. But here, the bond pads are placed opposite to each other and therefore existing bonding fabrication techniques are not applicable. To come around with this problem, we developed and produced a chip- and PCB-holder (Figure 7a). Both parts, chip and PCB are fixed by a vacuum inlet. During the bonding process, first the chip and PCB are wire-bonded together as they reside in one plane. After that, the chip was turned around in order to glue it onto the PCB. This turn-around process is complicated because the bond wires are not allowed to be stretched or extremely moved. The resulting chip-PCB compound is shown in Figure 7b. The bond gold wires of thickness 25 µm start at the PCB and go up to the chip pads. They can be seen in Figure 7b in front of the chip.

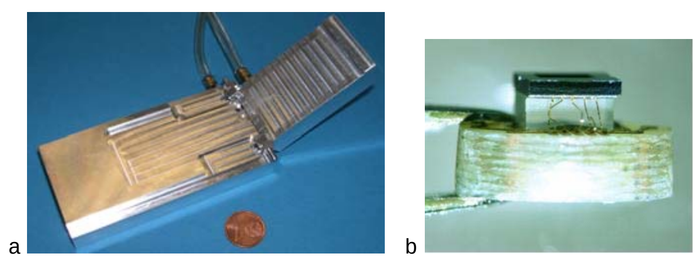

Figure 7. a) Chip bonding holder. b) Wire-bonded chip on the PCB compound.

The capsule steel enclosure with its tiny pressure transmitting holes (Figure 8a) is then pressed over the chip-PCB compound in order to protect the sensitive chip parts. The final sensor capsule with integrated cylindrical permanent magnet and seven electrical through-hole connections is shown in Figure 8b from bottom view.

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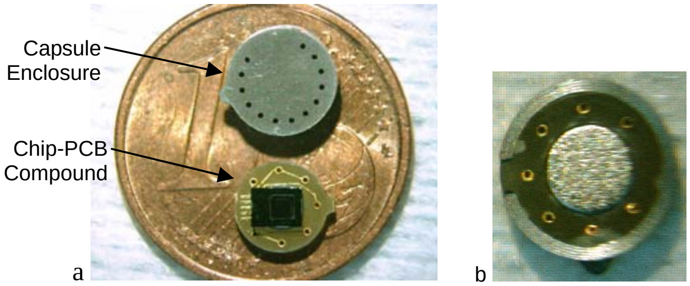

Figure 8. a) Size comparion of capsule enclosure and PCB with one cent coin as reference. b) Bottom view of the final sensor capsule to be inserted in the carrier.

Carrier

After the sensor capsule has been completed, the capsule carrier, also based on a FR4 substrate, is mounted. An identical permanent magnet is pressed inside the board and a steel frame is fixed onto it. The carrier (Figure 9a) contains neither pins for electrical connection nor screws or similar mechanical parts that are abrasion susceptible, just pads for electrically connecting between capsule and carrier and magnets for mechanical fixation. Furthermore the capsule can be easily placed inside the carrier. The completely mounted BVI pressure sensor is shown in Figure 9b.

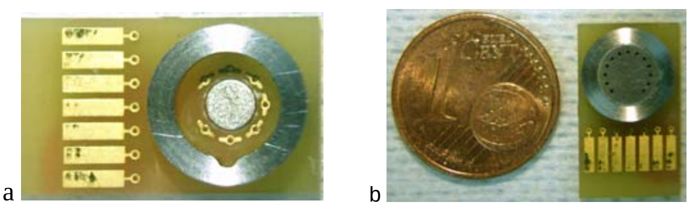

Figure 9. a) Robust sensor carrier ready for rotor blade integration. b) Completely mounted BVI pressure sensor in comparison to one cent coin

SENSOR RELIABILITY

The sensor will be integrated in rotor blades of helicopters for BVI detection. Due to its mature designed package it is robust against direct particle impacts. In case of dirt accumulation inside the sensor capsule it can be easily replaced, cleaned and reinstalled or completely renewed. The elastic foil furthermore seals the electrical connection pads between capsule and carrier from water intrusion. But dynamic loads caused by blade vibration are a major aspect of helicopter environment which may influence the sensor's performance and reliability. To test the sensor's behavior under these circumstances, vibration tests at amplitudes of 10 g and frequencies between 30 Hz and 10,000 Hz were performed. The sensor was fixed on a shaker setup and its output signal was recorded with a Labview program. The sensor signal curve over frequency is plotted in Figure 10. There are three main peaks, the first at 600 Hz with a value of around 2 %, another at 4 kHz with 4 % maximum and the last broad peak at 9.5 kHz has a fluctuation amplitude of 5.5 %. The BVI pressure that has to be detected is of magnitude 30 mbar at 150 - 250 Hz which is symbolically inserted into the graph. At this value, the sensor's signal fluctuation caused by vibration is just around 0.5 % and much smaller than the BVI signal. This means, that the sensor is very able to detect and magnify BVI occurrence even under dynamic loads.

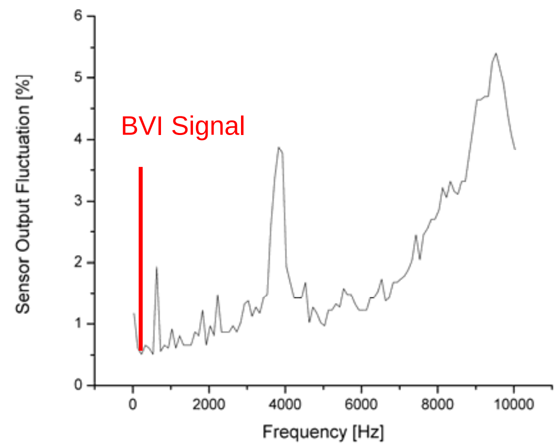

Figure 10. Sensor output fluctuation under dynamic load with 10 g amplitude

CONCLUSION

The presented sensor packaging concept is predestined for detecting BVI on rotor blades due to its robustness and simple replaceability. Thanks to MEMS based miniaturization, it can be mounted on even curve shaped surfaces. It possesses high reliability and robustness by combining high-tech packaging materials with unconventional mounting techniques.

ACKNOWLEDGMENTS

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