HELICOPTER ROTOR BLADE INTEGRATED TURBULENCE DETECTOR FOR NOISE AND VIBRATION REDUCTION MEASURES

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OVERVIEW

In special helicopter flight situations such as during descent flight, the main rotor blades frequently generate impulsive noise signatures resulting from the interaction of turbulence vortices and rotor blades. This is because the rotating blades usually generate trailing vortices which are pushed downwards during horizontal flight due to the blade downwash. But in special descent flight maneuvers, the blades also descent together with the helicopter and hit the downwash vortices which is commonly called Blade Vortex Interaction (BVI). This effect is characterized by high noise levels and structural vibrations that can be reduced with active control devices at the blade as response to turbulent fluctuations, identified and evaluated with an appropriate sensor.

A micro-electromechanical (MEMS) pressure sensor integrated flush into the airfoil surface is a very appropriate unit for BVI detection and characterization. This is because it directly measures the turbulence accompanying air pressure variations as the pressure is the most sensitive and reliable parameter to detect such interactions. Due to its micro size, it does not disturb the airflow passing the blade and does not need any complex signal processing units. Furthermore it can be operated with low power in the range of some mW.

This paper briefly describes the nature of the sensor and packaging concept and focuses on the rotor blade integration and the wind tunnel tests and experimental results.

1. MEMS BVI SENSOR

For the purpose of rotor blade turbulence detection, we presented a special pressure sensor based on MEMS technology for airfoil surface integration in [1]. The sensor is characterized by a robust packaging which makes it resistant against the influences in the harsh helicopter rotor blade environment, such as particle impacts, temperature and climatic extremes as well as high dynamic and static g forces with values up to 1000 g.

If the sensor has to be replaced or repaired in the case of hardware malfunction, it can be demounted and changed very easily in time-saving maintenance work because of its sophisticated two-component package (FIG 1). It consists of a sensor capsule and a carrier that is permanently integrated in the rotor blade. The carrier serves as a mount for the capsule and is constructed sufficiently robust that it never has to be replaced. The capsule contains the central sensing unit, namely the silicon chip. If it is congested with dust or dirt and a reliable pressure measurement is not possible anymore or if any of its parts is damaged, the capsule can be demounted from the carrier and a new or repaired one can be installed.

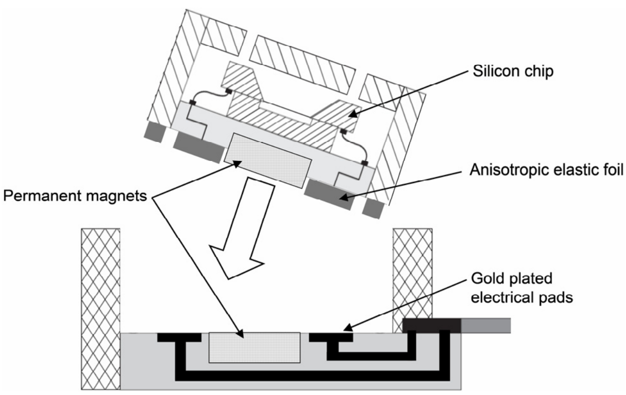

FIG 1. Robust and easy-maintenance two-component MEMS package for rotor blade BVI sensor. Top: Replacable sensor capsule. Bottom: Permanently installed carrier.

To facilitate this replacement process, the capsule is mechanically fixed inside the carrier with two tiny NdFeB permanent magnets which allow very fast demounting and mounting. The electrical connection between carrier and capsule is established by a silicone foil with anisotropic electrical properties. This makes pins or any other abrasive susceptible connections needless and it guarantees the realization of a permanently integrated, robust carrier.

Several environmental tests such as vibration and static g force tests as well as climatic experiments with the sensor and its robust package have proven its hardware functionality and operational reliability. Next, it was integrated in an EC145 rotor blade for further testing.

2. ROTOR BLADE INTEGRATION

The helicopter BVI case is mainly characterized by strong dynamic air pressure oscillations and peaks near the rotor blade leading edge [2][3]. Therefore, the most sensitive position for a BVI detection unit is the area close to the leading edge. The BVI identifying pressure peaks deplete and diminish in noise if the distance between detection position and leading edge increases towards the trailing edge [2][4].

This requirement defines the leading edge as the most efficient, while most sensitive installation location on the blade chord for a surface pressure sensor. As the leading edge is that part of the blade that is most exposed to particle impingements, it is usually covered by a metallic layer made of a special nickel alloy to protect the airfoil against material abrasion and erosion. This means the sensor faces the same harsh environmental conditions on the blade as the erosion protection layer and this is the reason why the sensor is constructed in such a robust way.

For further testing, we have installed the BVI sensor inside the erosion protection layer of an EC145 blade segment, as it is shown in FIG 2 and FIG 3. As can be seen, the sensor is located near the leading edge for establishing sensitive turbulence pressure measurements. The most important aspect during the installation process of the sensor was to remain the airfoil's original shape and surface flatness. This goal was achieved because of the low sensor size and by filling up the free space between sensor and airfoil with an adhesive.

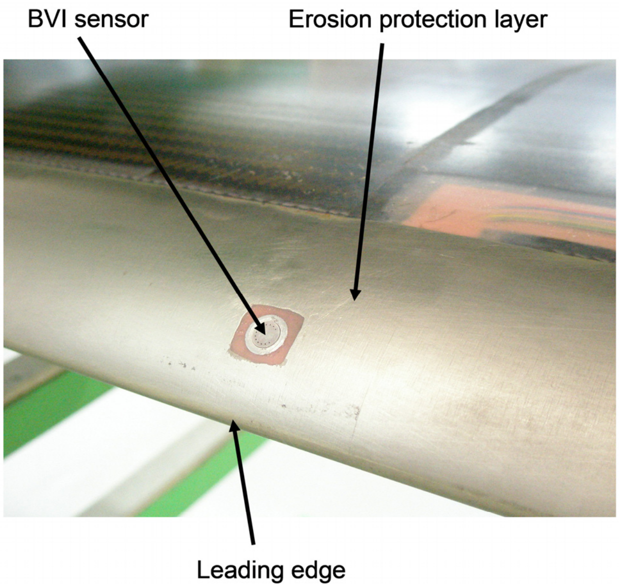

FIG 2. BVI sensor is located at the leading edge of the rotor blade inside the erosion protection layer.

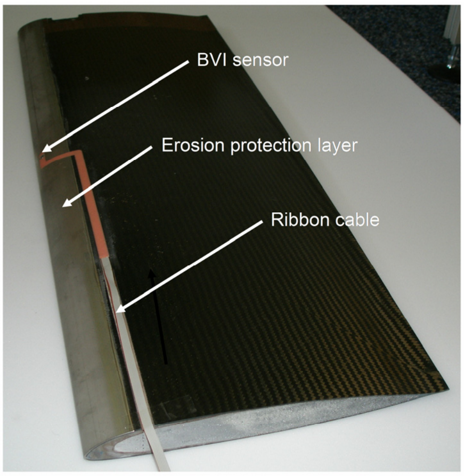

FIG 3. EC145 rotor blade segment with integrated cable wiring.

3. TURBULENCE PRESSURE MEASUREMENTS

The pressure sensor is mainly designed for detecting air turbulence on the helicopter rotor blade in order to improve the helicopter flight behaviour and to decrease the rotor blade emitted noise levels by active counter-measures. One main interest is that the sensor can resolve the dynamic pressure fluctuations accompanying the BVI cases. The measurements are performed in a wind tunnel facility B of the Institute of Aerodynamics at the Technische Universität München. The wind tunnel has a nozzle outlet of 1.55 m x 1.2 m. The maximum achievable air speed reaches 60 m/s which is below the rotor blade airflow speed but is sufficient for generating significant air turbulences. The higher the flow velocity, the higher are static and turbulence pressures. If the sensor is able to resolve pressure variations at low air speeds, it will be able to resolve them at high-velocity airflows like in the rotor blade during helicopter flight.

The EC145 rotor blade segment with integrated BVI sensor is used for the wind tunnel measurements. It is fixed inside the wind tunnel with a special rack (FIG 4). In order to get the actual flow velocity in front of the nozzle opening, a Prandtl's pitot tube is inserted. A microphone of type G.R.A.S. Type 40AE ½" prepolarized free field microphone as a reference sensor for the dynamic pressures is used and integrated in the set up. It can be lowered towards the rotor blade and any point on the blade surface can be evaluated with it.

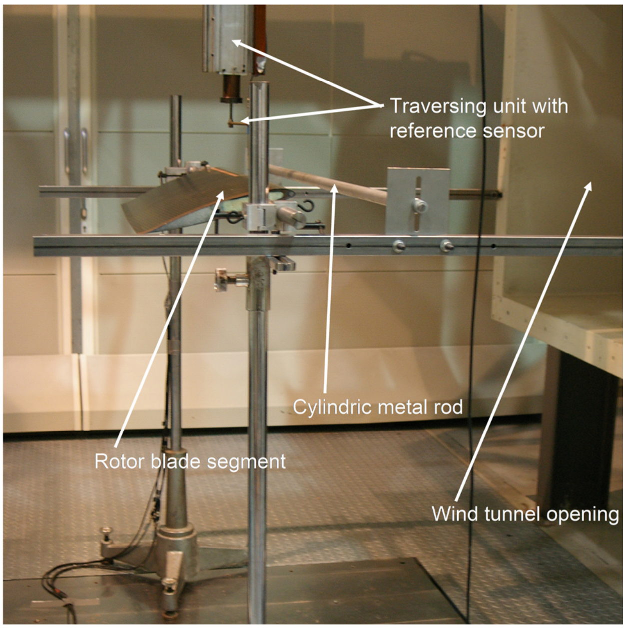

FIG 4. Wind tunnel turbulence measurement set up.

Flight tests have shown that the BVI induced dynamic pressure variations are characterized by a main frequency part that lies between 150 Hz and 250 Hz, depending on the flight conditions. Turbulences can be synthetically generated by a cylinder which causes the passing air flow to generate vortices on the cylinder's wake area (van Karman vortex street). The vortex frequency f depends on the Strouhal number Sr, the cylinder diameter d and the airflow velocity v by the following relationship [5]

$$(1) \qquad f = \frac{Sr \cdot v}{d}.$$

The frequency related to the shedding of dominant vortex structures is chosen to be around 250 Hz for the following wind tunnel measurements. With this frequency parameter, an approximated Strouhal number of around 0,16 and a maximum flow speed of 50 m/s, the cylinder diameter is set accordingly to 3 cm. The frequency decreases nearly linearly with lower air flow speeds.

The cylindrical metal rod is then mounted horizontally in front of the blade as shown in FIG 4 and the blade pitch angle is set to 6.1°. This adjustable configuration guarantees that the rotor blade lies within the cylinder's wake region and that it will be hit by maximum turbulences. The rotor blade and cylinder are then loaded with air velocities ranging from 15 m/s to 50 m/s. The microphone serves as the reference sensor and is installed right above the sensor in order to guarantee identical dynamic pressure levels on both sensors. A sample turbulence signal (without the constant 50mV DC contribution from static pressure) for an air velocity of 15 m/s is shown in FIG 5 in comparison to the dynamic pressure signal acquired from the reference microphone. As the microphone was calibrated, its signal is directly transformed into pressure values on the figure's right axis. It shows that the pressure amplitudes at an air velocity of 15 m/s are about 1,5 -2 mbar being clearly resolved by the BVI pressure sensor. In practice, real BVI turbulence causes dynamic pressure amplitudes of at least 6 mbar. This means the sensor is able to resolve dynamic pressures caused by turbulences significantly better than required.

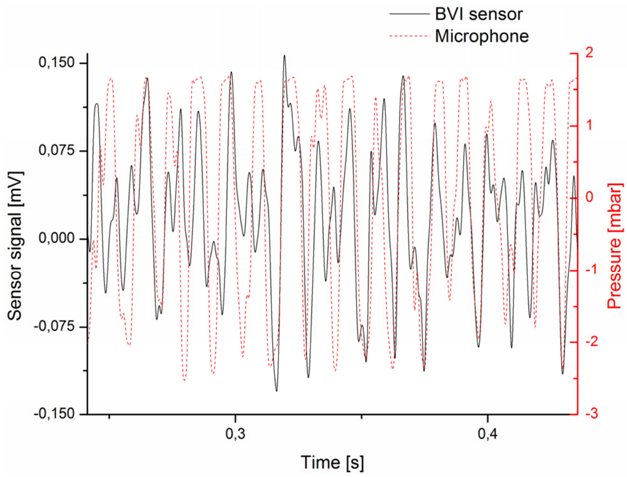

FIG 5. Turbulence pressure signal versus time for an air velocity of 15 m/s at 6,1° pitch angle of the rotor blade.

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The signal of the BVI sensor in FIG 5 shows some fluctuations originating from frequency components in the power supply as described below. The pressure amplitude spectrum is shown in FIG 6 for the interesting frequency range where the turbulence frequency is expected for an air velocity of 15 m/s in the example of FIG 5. The main peak bulk at 82,76 Hz in the middle of the graph represents the frequency spectrum of the air turbulence. According to Eq. (1), the theoretical value for the turbulence (vortex shedding) frequency is 81,28 Hz at 15 m/s, which agrees well with the measured frequency value. The peaks in the frequency domain of the BVI sensor at 50 Hz, 150 Hz, 250 and above are caused by the power supply and its higher harmonic components. The microphone has implemented a powerful preamplifier and a shielding concept which assures that this noise frequency is not transmitted to the measurement signal.

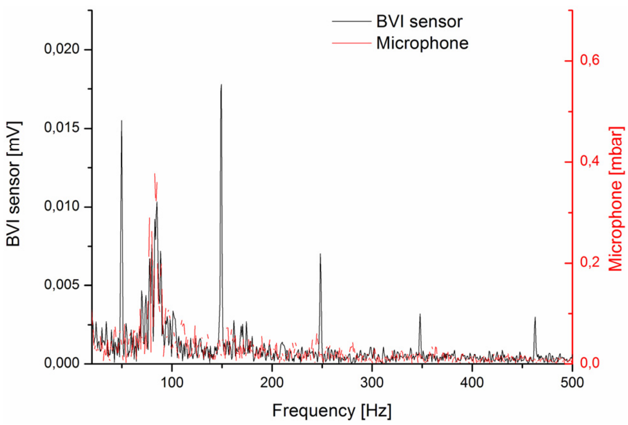

FIG 6. Turbulence measurement amplitude spectrum at 15 m/s at 6,1° pitch angle of the rotor blade.

Even if the blade pitch angle is changed from 6.1° to an extreme value of 16.2°, the BVI sensor can resolve the air turbulences as it is shown in FIG 7 for a flow velocity of 20 m/s. The parasitic frequency peaks at 50 Hz, 150 Hz, 250

Hz and above are also visible here. The turbulence content is represented by the peak bulk with its maximum at 112.8 Hz. The turbulence frequency is higher than the one at 15 m/s in FIG 6 due to formula (1) as well as the pressure amplitude which increases with increasing flow velocities.

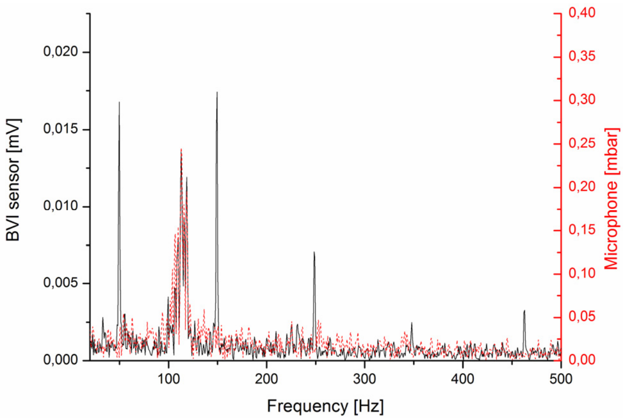

FIG 7. Turbulence measurement amplitude spectrum at 20 m/s at 16.2° blade pitch angle.

This dependence is clearly visible if the air flow velocity is set to 50 m/s. The amplitude spectrum of the dynamic pressure is shown in FIG 9. Because the microphone which served as the reference sensor for the former measurements is not usable anymore under this high-speed flow, a hot wire anemometer is taken for reference. Comparing the pressure amplitude of the peak maximum at 274.7 Hz with a BVI sensor signal of 0.115 mV to the value of 0.010 mV gained from FIG 6 for a flow speed of 15 m/s it is 11.5 times higher while the flow velocity just rises by the factor 3.3 from 15 m/s to 50 m/s. This means there is nearly a quadratic dependence between flow velocity and turbulence pressure amplitude.

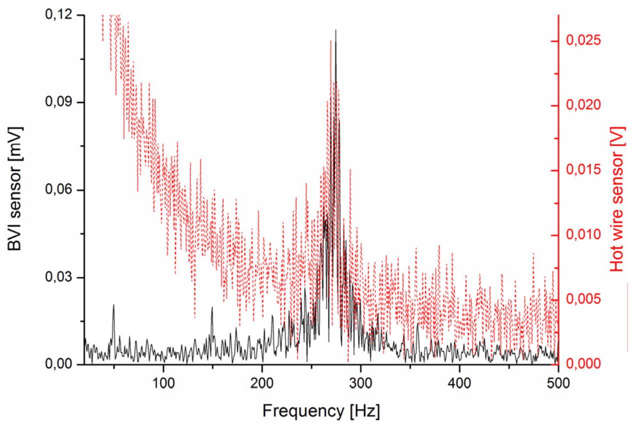

FIG 8. Turbulence measurement amplitude spectrum at 50 m/s at 6.1° blade pitch angle.

The relationship between turbulence frequency and flow velocity is shown in FIG 9 with a comparison of measured turbulence frequencies from BVI sensor and hot wire anemometer as reference sensor against the theoretical values based on a Strouhal number of Sr = 0.16. it is visible that the measured frequencies show a linear behaviour and correspond well with the theoretically predicted values.

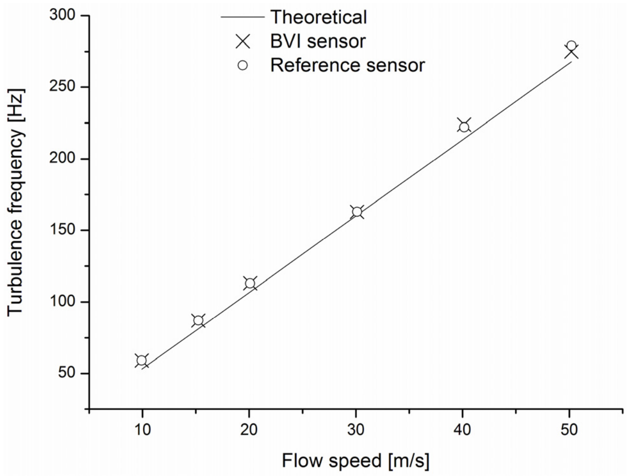

FIG 9. Comparison between measured and theoretical turbulence frequencies at different flow speeds.

The wind tunnel measurements have shown the sensor's potential to resolve even low level turbulence pressures in a high flow speed environment. E.g., as there is a sensor output signal of below 0,015 mV at a flow speed of 15 m/s for a pitch angle of 6.1° which is very small in comparison to the overlapped static pressure signal of around 50 mV resulting from the air flow pressure around the rotor blade. And if the pitch angle is set to an extreme value of 16.2° the turbulences can nevertheless be reliably resolved by the BVI sensor.

During real helicopter flight, the air flow around the blade is much higher than 50 m/s in the outer blade region where the sensor is located. This speed even causes higher turbulence pressure amplitudes than the ones which have been simulated in the wind tunnel facilities. It therefore will be easy for the sensor to detect and resolve these high-power vortices.

SUMMARY

The MEMS based turbulence sensor is integrated in an innovative two-component package. It is installed in the erosion protection layer of an EC145 helicopter rotor blade and has proven its usefulness for turbulence detection during wind tunnel measurements at the TU Munich. The fluctuating flow is generated synthetically by a cylindrical metal rod in order to simulate the main frequency part of BVI cases as they occur during real helicopter flights. It was shown that the sensor is able to resolve low turbulence pressures and that the generated turbulence frequencies can be reliably detected. Also, the measured turbulence frequencies at different flow velocities correspond well with the theoretically predicted values.

ACKNOWLEDGEMENTS

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