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Development of a technique for the detection and quantification of water and ice in the fuel tanks of an aircraft

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Abstract

During the daily operation, water can accumulate in the fuel tank of an aircraft. Freezing of this water during flight can result in unexpected situations during flight and on the ground. To reduce the risk of stuck mechanics or malfunctioning systems, the water is removed regularly. However, ice can be stuck in the tank if it is not removed by the normal procedures. To detect and quantify this, three different acoustic emission sensors are tested in a fuel tank model. Next to a classical piezo-electric setup, a Laser Doppler Vibrometer and an optical fibre setup are used to measure acoustic emission events during the melting of ice.

1 Introduction

Since the beginning of aviation, the ongoing development of new technologies and optimization of operational procedures increase the safety as well as the economical outcome of aerospace. While the number of yearly flights increases continuously since the commercial beginnings of aviation (2016 :> 32 million flights), the number of fatal accidents per million flight decreases to less than 0.5 per million flights since 2006. Besides the improvement of new aircraft (4th generation (fly-by-wire) aircraft), the improved operation of aging aircraft contributes to this positive trend of increased safety in commercial aviation. At the same time, the competition on the European as well as global aerospace market is increasing continuously and results in changes of the whole industry that are exceptional compared to other industries [1]. This results in an increased need of more efficient and economical aircraft operations. One of the requirements is the minimization of aircraft grounding time (down time) in which scheduled and unscheduled maintenance tasks are performed.

The need to minimize down times is a well-known issue for many aircraft operators and advanced water detection and finally draining procedures of aircraft fuel tanks to prevent water and ice accumulation in the tank system might provide interesting options.

2 Water in fuel tank

The problems that occur due to water in jet fuel and aircraft tanks are known since decades and described in several publications (e.g. [2]). Several articles target the presence of water in the fuel tank as such or discuss approaches to prevent its accumulation [3]. In general, water can appear in jet fuel in three forms, dissolved in the fuel, suspended in fuel as water-in-fuel emulsions, or as free water [3]. Spatially free water can starve engines, support microbial growth, contribute towards corrosion and furthermore freeze. The letter may harm structural elements within the tank and tank system such as valves, pipes or pumps. Either this damage is only temporal, so that is gone when the ice is melted. Or permanent damages that result in an expensive and time consuming repair. Both bring different problems in the daily work of pilots and aircraft technicians. The temporal freezing of tank components does not harm the structural integrity of the aircraft in a long-term manner. Nevertheless, temporary frozen components result in an unusual behaviour of e.g. the fuel level systems or problems concerning the opening or closing of valves in the fuel tank. These problems are reported to the respective Maintenance and Engineering departments that will check that reportings. It may happen that ice causing the malfunctions is already melted and everything works as expected. In this case, no malfunction is determined. In the other case, repair or replacement of the affected parts is required. In both cases accumulated free water freezes during flight (outside temperature below $-50°C$). The solid nature of ice as well as the thermal expansion of ice during freezing can lead to structural damages and system malfunctions.

To avoid ice formation, the presence of free water in the fuel tank must be reduced to a minimum. This can be done by reducing the water content of fuel that is used for refuelling, by fuel additives that keep the water in the fuel in the dissolved state and by physical removal of accumulated ice as often as possible. Even if the fuel used for refuelling is completely free of water, water accumulation in the tank cannot be prevented. To prevent a negative pressure inside the tank, a venting system allows a free air exchange between the inner part of the tank and the surrounding atmosphere. This air exchange happens during on the ground as well as in the air. With the air that enters the tank, espacially during descending, air humidity gets into the tank.

During the descent, the tank of an aircraft is almost empty and the atmospheric pressure increases the closer the aircraft comes to the ground. Both facts contribute to the fact that almost the full aircraft tank volume if filled with relatively warm and fresh air from the environment from the destination airport. After a flight of several hours in temperatures around$-50°C$, one can assume that the structure for the wing as well as the remaining fuel in the tanks is in this way below 0°C leading to continuous water condensation as long new fresh air flows into the tank.

Taking into account that an AIRBUS A330 wing tank has a volume of $45m^3$, up to 500ml of water get into the tank per flight due to air exchange between the inner of the tank and the surrounding atmosphere and the following condensation of the air humidity in the tank.

The different densities of ice (916 kg/m^3), water (1000 kg/m^3) and fuel (807 kg/m^3) result in layers of the three within the tank. In the case where Jet fuel, water and ice are present and free movable (ice not stuck to structural elements) in the tank, water is collected at the bottom of a basin, while the ice is swimming on top of the water covered by the jet fuel which is at the very top. Therefore, one can assume that whenever water is present in the fuel tank, it is at the very bottom of the tank.

There are two major possibilities to remove it from the tank that are currently used. Either small portions of water are sucked into the fuel system and evaporated

Figure 1: Left: Fuel pumps 1 and 2 with suction pipes (silver, facing towards viewer) which end at the lowest point of the wing. Right: Drain valve and suction pipe inside an AIRBUS A330 wing tank. The suction pipe connects the drain valve with the lowest point of the tank.

in the engine or the accumulated water is drained manually from the tank.

The suction of the water into the fuel system during flight is has several advantages compared to the manual draining of the tank as it happens permanently and requires no human action. But special suction pipes must be installed in the tank – installed by default in “new” aircrafts – and once free water is frozen at the bottom of the tank, it cannot be sucked anymore until all water is melted again. The suction pipes of an A330 wing tank are shown in figure 1 on the left side.

When no suction pipes are installed, big amounts of water can accumulate at the bottom of the fuel tank what requires the manual removal by technicians. This “draining procedure” is inter alia described in the AIRBUS Aircraft Maintenance Manual (AMM) and uses “drain valves” at the bottom of the tank. By opening the drain valves, any liquid can run out of the tank into a collection basin. Two problems occur regularly in the daily operation of these drain valves.

At several aircraft types (e.g. AIRBUS A320 and A330), the drain valves are positioned at the bottom of the tank but not at the very lowest point. Therefore, the water level can be too low and opening the drain valves does not result in a flow of water but fuel out of the tank. But not only water below the drain valve stays in the tank. Also frozen water remains in the tank when the draining is performed. Only when all ice is melted, the draining procedure reduces all possible water from the tank. Once free water accumulated in the tank, its freezing results not only in an inappropriate draining result but can also block drain valves and other mechanics.

To prevent the presence of ice in the tank after the draining procedure, one waits as long as possible after the landing until the draining so that the fuel and potential ice gets warm and is melted when the draining is performed. Especially at cold weather conditions, active heating elements like heating lamps or carpets are used to warm up the fuel whose temperature can be below $-10°C$ after landing. However, often the period between landing and draining is not long enough to warm up the complete fuel tank so that certain areas are still at sub-zero temperatures.

This is why it is desirable to develop a sensor system that is able to locate and estimate ice in the fuel tank so that operators have information about the ice in the tank before and after the draining procedure. This information can be used for optimizing the draining procedure, minimizing down times and increasing the efficiency of aircraft operations.

3 Experimental setup

The different physical and chemical properties of fuel, water and ice (density, viscosity, speed of sound, etc.) allow the distinction between the three with different measurement principles. But not all methods that may distinguish between the three materials in perfect conditions are applicable under the given circumstances.

3.1 Method

The goal is test three different AE measurement setups that might be used for the estimation of ice in an aircraft fuel tank from outside, possibly inside the tank. Possible methods should be applied in the hanger by technicians during daily operations. Therefore, the measurement must be easy to perform and carried out from the ground. As discussed above, the water and ice is sinking to the bottom of the fuel tank, therefore a measurement from the bottom plate is preferred anyway.

One of the possibilities to detect ice is acoustic emission (AE) measurement. This technique has several advantages towards other non-destructive methods like thermographic imaging or ultrasonic inspection. Many articles give good overviews of the theory and diverse applications of AE and a detailed explanation of main parameters. (e.g. [4], [5], [6]). Next to applications in engineering (e.g. [7], [8]), other applied fields are food science [9], medicine [10] and machine monitoring [11]. Boyd [4] concludes the possibilities of using passive acoustic emission for "chemical engineering processes" and gives a good introduction into the measurement principles, analysis and machineries. The general measurement setup for a passive acoustic measurement includes the acoustic sensor, followed by the filtering and amplification of the signals and a signal analysis [4]. Every part of this measurement chain can be realized in different ways and depends on the application (costs, usability and needed sensitivity) and the other components.

In this paper, three different measurement setups and the parallel measurements of different acoustic events will be discussed.

3.2 Setup

As discussed above, the setup of a passive acoustic measurement always consists of sensors, the filters and amplifiers and a signal analysis unit (e.g. [12]).

Here, only a short introduction into the measurement principles of the different setups is given. In any case, the sensor is the part of a measurement setup that converts a surface motion into an electrical signal. However, several unavoidable artefacts modify every analogue electrical signal. This includes electromagnetic noise, damping and filtering of the signal in every passive or active element (cables, amplifiers, filters) in the electrical path.

After the analogue signal processing (filtering and amplification), either the full wave forms within a certain time window or specific signal parameters, such as "counts" are recorded. In the case of full waveform saving, a range of digital signal processing techniques can be applied afterwards.

The three different measurement setups used in this paper differ in the type of sensor as well as in the signal processing and will be described in the following.

3.2.1 Piezo Electric Setup

The most common AE sensor is a piezoelectric (PZT) sensor that transforms elastic motions into voltages in the µV range [12]. These sensors exist in many different variations that come with different frequency responses, gain factors and physical dimensions. In this experiment, the commercial broad band piezoelectric sensor "*VS30-V*" from the Vallen with a frequency range of 25 to 80 kHz is used [13].

The output signal of the PZT sensor is recorded with a digital oscilloscope (*Tektronix DPO 4034*) without any analogue filtering or amplification.

3.2.2 Laser Vibrometer

The second set-up is using the commercial Laser Doppler Vibrometer (LDV) *Polytec OFV-505* sensor head with a *Polytec AFV-5000 Vibrometer Controller* [14], [15] which is operated in the Velocity mode. The LDV is based on the Doppler Effect that uses the interference of a back scattered laser beam and a reference beam. A good review of the current status of this technology that is used since the 1880's can be found e.g. in Castellini [16].

3.2.3 Single-Mode Optical Fibre (OPT)

In the third setup, a single mode (SM) optical glass fibre is used as a sensor (*Molex FIP100110125*, 100 um core). The detection principle is based on the change in isotropy of the fibre when exposed to bending, stress or vibration. To measure this, a stabilised laser source (*Ando AQ-4141B*) is used to send polarised light (continuous-wave) with a wavelength of 1310 nm through the optical fibre. After passing a polarisation filter, the two modes interfere and the resulting signal is converted into an electrical signal with a photo diode.

In general, the fibre is of an isotropic nature so that the two linear orthogonal modes propagate through the fibre at the same velocity. This changes when the acoustic waves are arriving at the fibre and it becomes anisotropic. In that case, the velocities of the two linear modes change causing a phase shift and signal change at the photo diode. This setup is already used in several experiments dealing with acoustic emission detection (e.g. [17]) The sketch of the setup is shown in figure 2 where the parameters of the applied filters are shown as well.

The three different setups come with several pro and cons. The PZT setup is the most common setup in AE measurements. The signal-to-noise ratio of these systems are highly appropriate in many cases. The LDV system, other than the PZT system, can work however contactless. Although, for reasonable far distance measurements with a red light laser, the test piece has to be equipped with e.g. a reflective tape which might be problematic when it comes to aircraft skins. In addition, the costs of commercial system are very high. Other than the other two, the OPT system must be permanently installed at the inspection area. Due to the non-electric nature of the sensors (optical fibres) this is even possible in the fuel tank of an aircraft. However, for a commercial application of the OPT system, the signal-to-noise ratio and the costs this system has to be improved.

To test the three sensors in realistic circumstances, a tank model is build. This model is made from the same material as the tank bottom plate of an AIRBUS

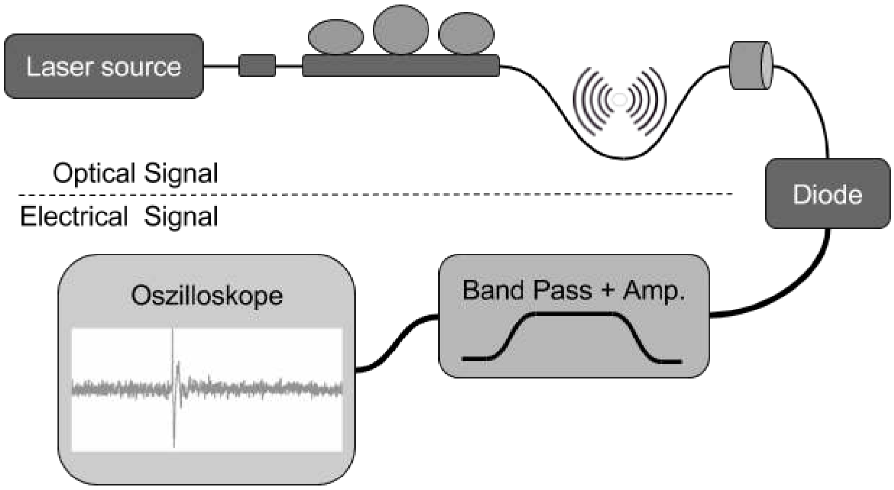

Figure 2: Scheme of the Optical Fibre setup. The Laser light (wavelength: 1030 nm) propagates from the Laser source (type Ando AQ-4141B) through a manual polarization controller (Fibre Control Industries FPC-3) followed by the SM optical fibre and a polarisation filter. After that, the light signal is converted into a voltage signal with a photodiode. Afterwards, the signal is filtered and amplified (Krohn-Hite model 3988 LP/HP dual channel filter, applied band-pass-filter: 0.1 - 20 kHz, gain: 50 dB) and finally digitalised with an Oscilloscope (Tektronix DPO 4034).

A330/320 (AL 2024/T3) and has a thickness of $d = 8\,\mathrm{mm}$ what is in the order of the real bottom plate thickness. The inner dimensions of the tank model are $100\,\mathrm{cm} \times 50\,\mathrm{cm} \times 20\,\mathrm{cm}$ and the edges are sealed with a silicone that is also used in real aircraft tanks. For testing the three different sensor methods, one litre of frozen water is used as acoustic source.

Figure 3: The three different sensors used in the experimental setup. The piezoelectric sensor, the Laser point on reflective tape and the Optical fibre glued to the AL plate. On the right, the stand for a mirror that guides the laser beam of the LDV on the plate is seen.

4 Results

In figure 4, two acoustic signal from melting ice are shown (left and right) measured with the three different methods – PZT (top), Optical Fibre (middle), LDV (bottom). Due to the different methods and the respective filtering and amplification procedures (see 3.2) the parameters of the signals (absolute signal amplitude, noise level (signals at negative time $t < 0$) and the signal shape/envelope differ significantly. To increase the signal-noise-ratio, a digital low-pass/band-pass filter

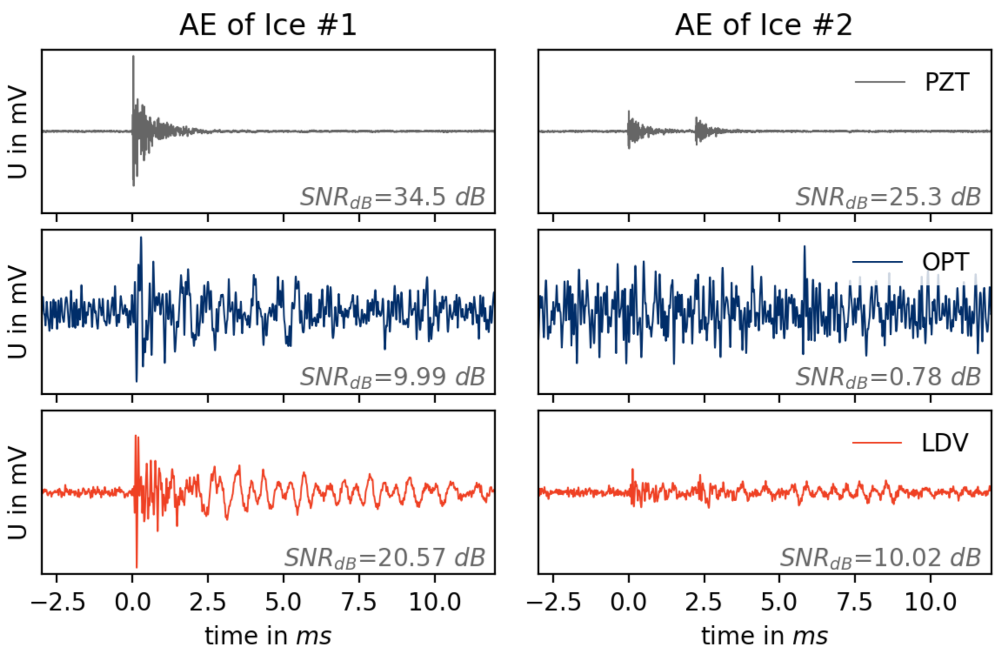

Figure 4: Two AE signals with different energies emitted by melting ice, detected with three different measurement methods and filtered with analogue and digital filters. (Digital filters: PZT: low-pass 80 kHz, OPT: band-pass 0.5 - 13 kHz, LDV: band-pass 1.5 - 18 kHz)

(Butterworth) is applied to the signals.

Several acoustic events during the melting of ice are recorded with the three sensors simultaneously. However, here the signal energy distribution does not correspond to the distribution of signal energies of a usual melting process. The low energetic events ($U_{pp,PZT} < 20\,mV$) are much more frequent.

For further analysis, the signal amplitudes of the OPT and LDV measurements are plotted against the PZT signal amplitude. Because the PZT measurement is the most sensitive methods with the highest signal-to-noise ratio, its signal was used for triggering and the amplitude served as a reference. The respective data are shown in figure 5. In addition to the acoustic events, the noise level and the respective 1 sigma surrounding (shadowed area, explain sigma) of the LDV and the OPT setup are shown. The noise level of each channel is estimated by measuring the peak-to-peak level before the acoustic burst and shown in figure 5. The dotted lines are just guides for the eyes, representing in a first approximation of the linear relationship between the signal peak-to-peak apmplitudes of the OPT and LDV waveforms and the PZT amplitudes respectively.

5 Discussion

In figure 4, two typical AE events measured with the three different methods are shown. In the PZT channel (top), both signals are clearly visible and have a peak-to-peak amplitude of $U_{pp} = 385\,mV$ and $U_{pp} = 111\,mV$ respectively. Due to the very low noise level of the PZT channel that mainly depends on the Oscilloscope setting and the voltage range, the signal-noise-ratio (SNR) are very high. Due to the high frequency range of the PZT sensors, the response of the sensors to the acoustic event is fairly short ($t \sim 2.5\,ms$) and the two burst in event #2 can be distinguished easily.

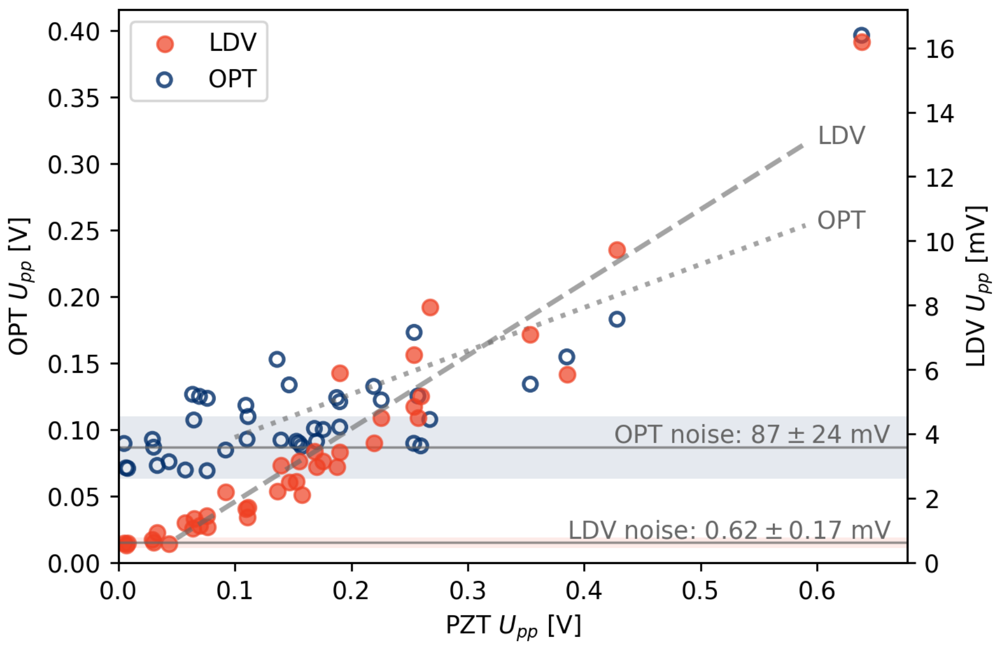

Figure 5: The peak-to-peak amplitude of the LDV (red) and OPT (blue) setup during the acoustic event detected with the PZT setup plotted against the reference signal from a PZT.

In the OPT channel, only the first event is visible. This is because event #2 has a lower energy (taking the PZT signal as a reference) and the noise level in event #2 is higher. Therefore, the lower response of the optical fibre setup disappears in the noise signal.

In figure 5, the peak-to-peak amplitude of the LDV and the OPT setup are plotted against the PZT amplitude. The LDV amplitude shows a dependency on the PZT amplitude and a linear behaviour above its noise level which is given the selected parameters around $U_{noise,LDV} \sim 0.6\,mV$. However, within a more elaborated analysis, the linear response of the LDV and OPT setup with respect to the acoustic energy of the evets should be investigated.

The OPT setup does not show a clear linear response. This might have different reasons such as different frequency characteristics and experimental boundary conditions. In addition, the noise level is not only higher compared to the highest signal amplitude but also shows a higher variance.

6 Conclusion

Three different measurement setups for the detection of (melting) ice with acoustic emission are investigated. Clear signal responses with all three methods (PZT, OPT, LDV) are measured. However, the signal-to-noise ratios differ significantly as expected and real low energetic signals cannot be measured with the OPT or LDV setup. By reducing the noise level, especially of the OPT setup, the technologies might be suitable for ice detection in aircraft tanks due to its advantages explained in section 3.2 given that a significant number of events representative for the whole population can be detected.

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