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# ULTRASONIC TECHNOLOGY :
# A SOLUTION FOR IN-FLIGHT AND ON-GROUND ICE DETECTION.

Michel LE PIMPEC
R&D Manager
INTERTECHNIQUE
Plaisir, France

## Abstract

Detecting in-flight ice accretion on aircraft and measuring the effectiveness of anti-icing fluids before take-off are two major issues that are of prime importance for flight safety.

Ultrasonic waves associated with a proper signal processing provide a powerful and effective mean to analyze the wing surface and to provide the pilot with accurate information related to icing events

This paper describes the issues to address while the aircraft flights or is on ground before taking off, the principles used for designing an ultrasonic ice detection and fluid monitoring system and, through the results of the related experimentation demonstrates the cogency of this technological approach.

## 1- Introduction

Ultrasonic waves are well known for their capabilities to test materials. They have the interesting property of penetrating into the them and of reflecting differently on the various layers and structures met on their trajectory. Analyzing the resulting reflected echoes provides accurate informations about the material and the structures encountered by the waves.

Many applications of ultrasonic technologies are known in various areas such as in medical sciences (echography), industry (non destructive testing of materials), process monitoring (chemical or nuclear industry) and many others.

Intertechnique engineers have successfully applied these techniques to the design of airborne sensors able to alert the crew in case of in-flight icing and/or unsafe anti-icing protection before take-off.

## 2 - Application to in-flight ice detection

### 2.1 - The problem of in-flight icing

It is well known that an aircraft can accrete ice when flying in specific meteorological conditions characterized by a set of parameters (temperature, air pressure, air humidity),. In most cases, ice accretes on the leading edges. The accretion may be of different shapes depending from the local values taken by the above parameters. This kind of icing is generally called "Appendix C" icing by reference to the Appendix C of the FAR/JAR 25 which describes the values of the parameters for which such icing may occur.

In case of very specific meteorological conditions characterized by large droplets of water in supercooled conditions, ice may also accrete at other locations than on the leading edges. This kind of icing is generally called "SLD icing", with SLD standing for Super Large Droplets or Supercooled Large Droplets.

Because of the aerodynamic consequences on the flight characteristics, aircraft icing is known as being a very hazardous event which requires immediate

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action from the crew. In case of Appendix C icing, the crew must de-ice the leading edges. Various means are used for that purpose (heating of the leading edges by hot air on jets, rapid air inflating and deflating of pneumatic boots covering the leading edges on turboprops). In case of SLD icing, the only solution, since ice protection systems cannot cover the entire surface of the wing, is to leave immediately the hazardous area, which, fortunately, is generally quite small.

It is clear that, before any further action and in any case, the crew must be informed about the icing event. This necessary function requires ice detection for which many means have been imagined, from the simple visual information (icing of the windshield wiper nut) to sophisticated devices such as the one we are going to describe.

### 2.2 - Basic principles for the ice detector

The ice detection sensor principle is based on the principle or determining the nature of a material by measuring its acoustic impedance.

Let us remind that the acoustic impedance of a material is given by :

$$Z = \rho.v \qquad (1)$$

where $\rho$ is the volumetric mass of the material and v is the velocity of the sound in this material.

| Material | Acoustic impedance (Mrayls) |
|---|---|
| Air | $4.1\ 10^{-4}$ |
| Water | 1.5 |
| Ice | 3.6 |
| Polymer (PEI or PSU) | 2.8 |

If an acoustic wave propagates from a material [1] to a material [2] respectively characterized by Z1 and Z2, this wave splits at the border into a reflected wave and a transmitted wave.

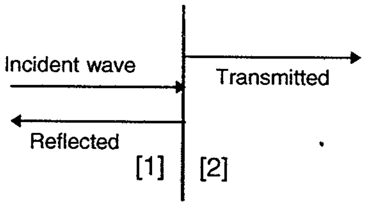

FIGURE 1 - Splitting of ultrasonic waves

The reflected part of the incident wave is :

$$r = (Z1 - Z2) / (Z1 + Z2) \qquad (2)$$

The transmitted part of the incident wave is :

$$t = 2.Z2 / (Z1 + Z2) \qquad (3)$$

A simple ice detector can be built, taking profit from these above relations.

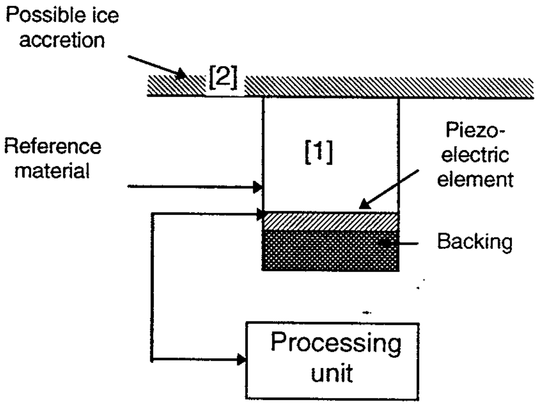

FIGURE 2 - Simple Ice Detector

In the figure 2, the material [1] is a reference with a well known acoustic impedance Z1. We have chosen a polymer (PSU or PEI). The material [2] is unknown and we want to determine it, but we know that in our specific application (detection of in-flight icing) it can be air, water or ice. Referring to the previous acoustic impedance values and to [2], one can calculate the possible values :

| Material [2] | Coefficient of reflection |
|---|---|
| Air | 1 |
| Water | 0.30 |
| Ice | -0.19 |

If an acoustic pulse is sent from [1] to [2], the reflected echo will have the following shape depending from the nature of [2].

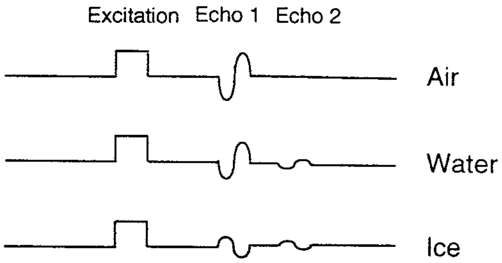

FIGURE 3 - Echoes shape

The first echo comes from the material [1] / material [2] border and will differ in amplitude and in phase depending from the material [2] nature. It is interesting to observe that the reflected echoes coming from a clean surface or coming from ice have roughly the same amplitude but an opposite phase. This feature simplifies the further signal processing and is the result of the choice of [1] with has an acoustic impedance Z1 comprised between Zair and Zice.

The second echo comes from the material [2] / air border and is of a particular interest to go one step beyond the simple detection of ice.

Knowing the velocity of ultrasonic waves in ice (3 980 m/s), it is easy to determine the ice accretion thickness, and, by taking the first derivative of this value versus the time, the ice accretion speed. Both data, are representative of the importance of the icing phenomenon and may help the crew in having a better view of the situation.

Much of this very preliminary work has been done by ONERA and has resulted in a patent granted to Intertechnique. However, producing and receiving an acoustic wave with the same transducer and with so short paths is quite difficult because of the transducer recovery time once it has been excited. This is one of the reasons which have led us to chose a different geometry with two transducers, one acting exclusively as a transmitter and the other exclusively as a receiver. It can be demonstrated that, as a first approximation, the above principles of operation and relations remain valid.

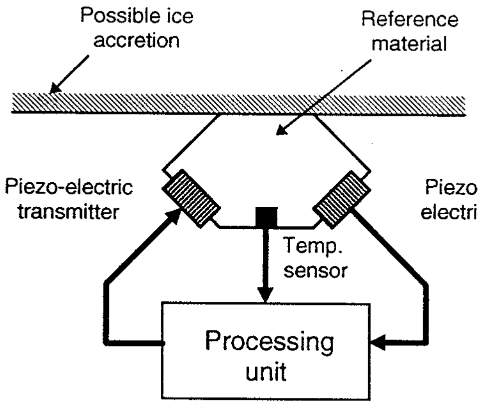

FIGURE 4 - Enhanced ice detector

Such an ice detector has to be placed at the adequate location(s) of the aircraft, depending from the kind of accretion it is intended to detect :

- on the leading edge for detecting Appendix C ice accretion,
- aft the leading edge for detecting SLD ice accretion,
- on the empennage for detecting tailplane icing,
- at any other critical location depending from the aircraft and the specific accretion to detect.

Of course, such an ice detection system may comprise several sensors placed at different locations and reporting different kinds of icing to the crew.

## 3 - Application to on-ground ice detection

### 3.1 - The problem of on-ground icing

The operational problem of on-ground icing is less obvious than the problem of in-flight icing. In fact, two subproblems exist:

#### 3.1.1 -Initial icing

If an aircraft stays outside with icing or snowing conditions it becomes iced and/or covered with snow. It is hazardous and forbidden by the regulation to take-off with an aircraft in such conditions. Regarding these situations, the only solution is to de-ice the aircraft.

The first problem is to determine the necessity of deicing the aircraft. Detecting snow on the aircraft is obvious and can be done visually, but it is much more difficult to determine whether aircraft surfaces are covered with ice. In bad weather or night conditions this determination may become nearly impossible. Only a careful and even tactile inspection can lead to a correct conclusion. To address this issue, at least two equipment suppliers have recently developed infrared cameras based systems which greatly help by providing a false color image to the de-icing team. This image clearly shows the iced areas and then where to apply a de-icing fluid, generally glycol based.

#### 3.1.2 - Protective fluid efficiency

A deiced aircraft may remain safe for a long time if it is not raining or snowing, and can then be operated safely. However, in case of precipitation, a new icing may occur, sometimes very rapidly, leading to the impossibility to take-off. A new de-icing is then necessary.

Specific fluids called anti-icing fluids, also glycol based, are used to avoid this situation. In case of bad weather, a layer of anti-icing fluid is applied on the aircraft after deicing. This layer, also glycol based and quite viscous avoids the snow or the rain to freeze on the aircraft surface. Snow or rain are absorbed and dilute the anti-icing fluid. The protective fluid layer flows off from the surface when the aircraft takes off.

A great improvement in brought to the winter flight safety by using these anti-icing fluids. But, it is clear that the protection provided by the anti-icing fluid is limited in time. The fluid being more and more diluted by the precipitation, it turns progressively into water and, if the temperature is low, into ice.

Then the question is : *"How much time will the anti-icing fluid protect the aircraft ?"*

and the answer is : *"From 3 minutes to several hours depending from the nature and the rate of the precipitation, the temperature, the initial dilution of the fluid when it is applied and other parameters".*

Pilots have been provided with tables to help them determining the fluid efficiency duration time (also called the holdover time). But even if these tables are carefully built and try to address the widest range of situations, they cannot report all of them. Therefore, they cannot provide more than rough estimations of the fluid efficiency duration time.

### 3.2 - Use of the ice detector for measuring the fluid efficiency

We have said in the previous paragraph that the anti-icing fluid will remain efficient, providing that it will not turn into water and then into ice. In fact we are speaking about the freezing characteristic of the anti-icing fluid.

Let us consider the following chart where the Y values represent the fluid temperature and the X values the fluid dilution.

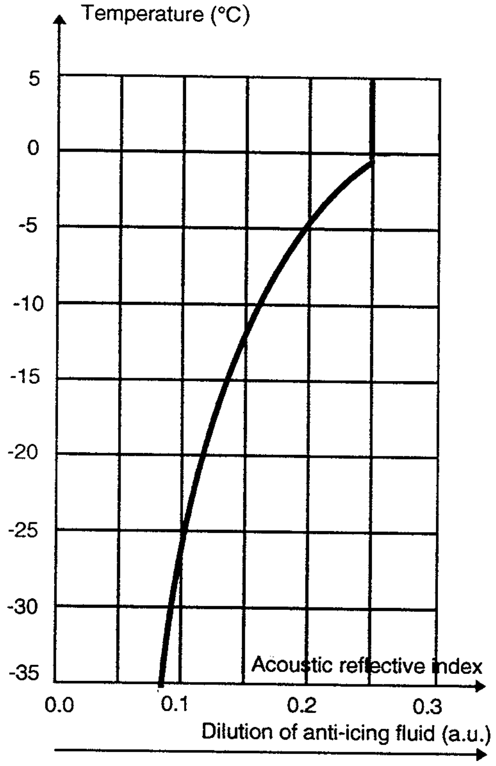

FIGURE 5 - Freezing point chart

The left side of the graph represents the [temperature / fluid dilution] domain where the fluid is liquid, and provides then a protection, whilst the right side represents the [temperature / fluid dilution] domain where the fluid is frozen. The temperature and the dilution rate of the fluid are the necessary and sufficient parameters to know whether a fluid is efficient or not.

The above described enhanced ice detector can be used as it to determine the fluid dilution rate. In fact an experimentally established relation exists between the fluid dilution rate and the reflection coefficient of the incident wave at the sensor / fluid border. The fluid dilution rate and the temperature being measured provided by the sensor, it becomes possible to know the status of the anti-icing fluid from the above chart.

Moreover, the detection of ice and the measurement of the thickness of fluid or ice can be provided in the same way as for in-flight ice detection.

After processing of the data, the following information are provided to the pilot :

- UNPROTECTED WING
  if the fluid thickness is < 0.1 mm
- FLUID
  if the fluid thickness is > 0.1 mm an its temperature at least 5°C above the freezing curve
- DEGRADED FLUID
  if the fluid temperature is closer than 5°C to the freezing curve
- FLUID FAILURE
  if the fluid temperature as reached or crossed the freezing curve
- UNSAFE
  if slush or adhering contamination are detected, even if the ice layer is above the fluid.

## 4 - Practical experimentation

Many practical experimentation have been done to verify the behavior of this ice detection system :

### 4.1 - For in-flight icing :

- Climatic chamber
  - Intertechnique, France
- Icing tunnels
  - CEPr Saclay, France
- Flight tests
  - ATR72 behind a water spraying tanker, Edwards AFB, USA
  - Transwede Fokker 100, Sweden
  - Airbus A340 test aircraft

### 4.2 - For on-ground icing :

- Climatic chambers
    - Intertechnique, France
    - AMIL, Chicoutimi, Québec, Canada
- Outdoors tests on test benches
    - Copenhagen and Swedish Airports
    - AMIL, Chicoutimi, Québec, Canada
- Flight tests
    - Transwede Fokker 100, Sweden

All these tests have demonstrated the excellent behavior of this ice detection system, in flight as well as on ground.

## 5 - Conclusion

Once more, ultrasonic technologies have demonstrated their capabilities in solving a non trivial problem.

The result is a unique system able to provide in-flight and on-ground ice detection and to monitor the anti-icing fluids effectiveness.

Many verification tests have led to the conclusion of an excellent behavior in a wide range of situations.

This successful research has resulted in a product called WCMS (Wing Contamination Monitoring System) now available from Intertechnique.