Measurement of Ice thickness on Airplane

Am sure, natural icing and deliberate deicing are terms all of us are familiar with. Closely associated with this is measurement of ice layer’s thickness in first place. How is it accomplished?

“UTC Aerospace Systems ice detectors use a **magnetostrictive technology to drive the sensing probe to resonate at its natural frequency**. As ice accretes on the probe, a shift in resonance frequency occurs. When the resonance frequency reaches the set point, an ice signal is activated and the strut and probe de-ice. **UTC Aerospace Systems' vibrating probe ice detectors** are the only systems certified for primary use on commercial transport airplanes by the FAA.”

In this article we attempt to understand the thought process behind this inventive solution to an important safety related problem in aviation.

Initial situation, viz. before ice measurement systems were in place

Modern passenger planes cruise at altitudes where temperature of air dips as low as -50C. The plane becomes covered with ice crust, heavier and more significantly aerodynamically unstable and thus unsafe. Therefore the heating system of the plane surface is turned on long before the approach of critical icing. For this, hot air from engines is easily used. Quite a lot of power got wasted in this schedule. Why? The paradox consists in fact that a small layer of ice (up to 0,1 mm) *improves* aerodynamic characteristics of plane and therefore reduces fuel consumption. It would have been good to turn on heat only after excess of this ‘good’ thickness. For this, it was mandatory to continuously define ice thickness in real time and to only turn on heating at correct time and then to turn off it at correct time?

Problem to define ice thickness was complicated by variation in thickness at different sites of the plane covering: ledge, deepening, corner, in place of change in cross-section. All these locations command lowest temperatures and lowest speeds of air.

Thought process which led to technical solution (most likely!)

Covering of plane is quickly cooled and moisture condenses on it from atmosphere. Icing begins. The layer of ice of up to 0.1 mm is not dangerous. If the layer is thicker then heating should turn on. If it is less, it should turn off.

Functional Performance (FP) or Most Useful Function(s) of system: it is necessary to measure thickness of ice in order to turn heat on/off in time. Thus the initial problem is measurement of ice thickness.

Technical System (TS) for measurement of ice thickness includes covering of the plane and the ice formed on it, settling from a counter stream of air.

To proceed, a contradiction (Technical or Physical Contradiction) must be formulated before it is resolved. We call it TC or PC.

TC can be only between interacting elements of system. Here such interaction can be only exist between the measuring tool and object of measurement (ice). However, the measuring tool is missing.

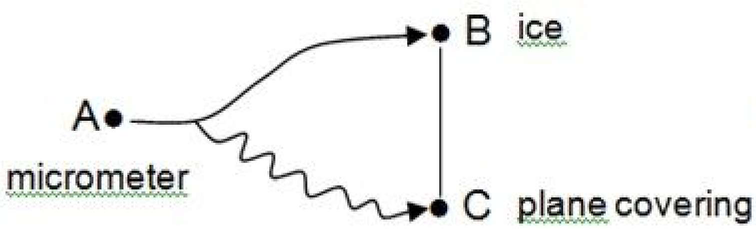
It is thus necessary to complete system with any known way of measurement, no matter how elementary. What come to our head first? How to measure a thickness of 0.1 mm and less? Standard instruments, like a ruler, a micrometer spring to our mind.

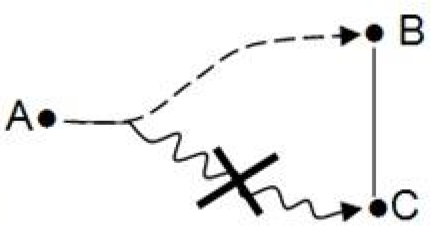
Here is the TC:

Option A: If there is a micrometer, ice thickness is measured, but the coverings of micrometer destroy the ice itself.

Option B: If there is no micrometer, then the covering does not destroy ice, but then thickness of ice is also remains unmeasured.

Conflicting pair: product – ice WITH tool – micrometer.





Let us reconfirm the sequence of events **if Option A is adopted.**

- The plane has took off, has reached the cruise height and the icing began
- Continuous measurement of ice thickness begins,
- At achievement of thickness 0.1 mm, heating of coverings' turns on,
- At reduction of thickness less than 0.1 mm heating is turned off,
- It achieves an overall objective – safe & economical (fuel saving) flight.

To measure ice thickness, micrometer has to cut across wing or other structure. Since hole is unsafe, this scheme is declined!

We hence choose **Option B - the measuring tool is not present !**

Step 1 : Intensifying Technical Contradiction : thickness of ice is continuously measured by some unknown tool very efficiently. It is done by a mysterious element, say U (Unknown). It is necessary that U constantly measures variable ice thickness, without damaging the ice layer itself, as latter can be fragile.

Step 2: Space of Operation: SO:

- layer of air near the plane covering (specification: quickly moving air),
- covering,
- ice.

Step 3: Time of Operation: TO:

-during all flight
(The Time of Operation actually includes pre-conflict time, conflict time (when challenge faced) and post-conflict time. In other words, it is before, during and after challenge durations added. Herein conflict time is same as TO because we are facing measurement challenge entire time.

Step 4: Substances-Fields Resources available including idle or free resources.

Substances: - ice,
- air,
- covering.

Fields: - Force: a mechanical field of air
- Force: mechanical vibration of the covering generated by working engines.

Step 5: Ideal Final Solution: IFS: U at all not complicating the system and not causing the harmful phenomena provides continuous measurement of ice thickness by exploiting SFR.

Step 6: IFS- Intensified

- it is impossible to enter new substances and fields
- in list of SFR, we add changed substances and fields already available. This means we can have changed ice (thickened ice) itself as part of SFR.

Step 7: Here comes the real step. Use the resource(s) which is changing or changeable to proceed.

Air? - it is impossible to change (we couldn't change it on all planet).
Ice? – it is constant in Technical System (TS) and is coming from the outside, it is impossible to change it.
Force of stream? – it depends on speed of work of engines, it is impossible to change it.

Vibration? - the same.
Covering? - it is impossible to change it.

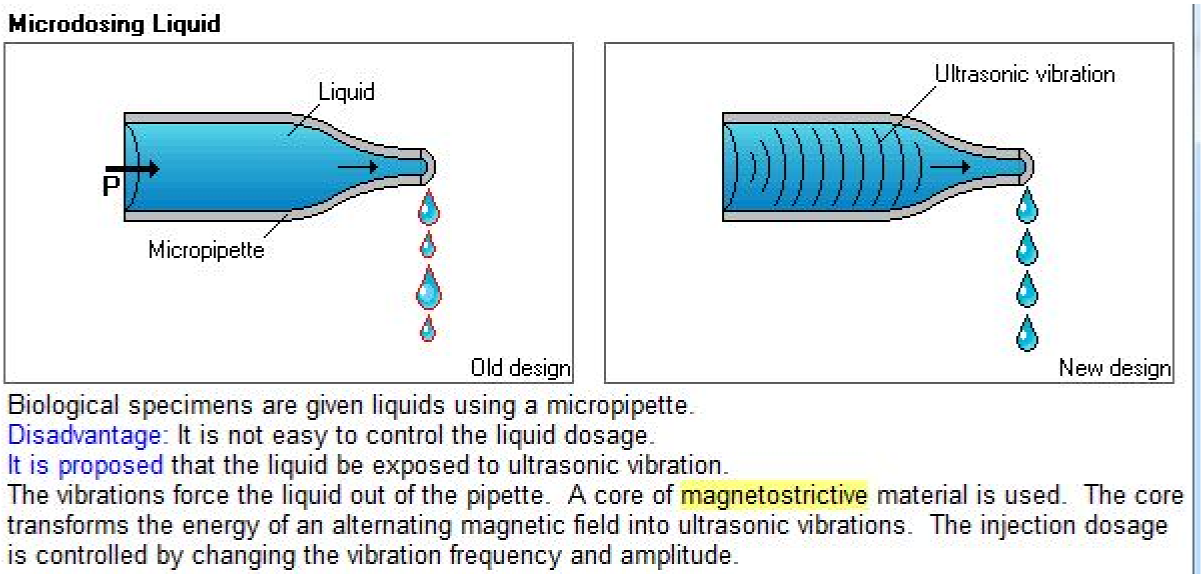
It appears that there is no changeable resource in our SFR list. This is our analysis at macro-level. However, at closer thought, **ice emerges as a changing resource.**

Step 8: IFS: Final: U at all not complicating the system and not causing the harmful phenomena provides continuous measurement of ice thickness by exploiting ice of changing thickness. In other words, ice measures itself!

Step 9: List all properties of ice that are changing other than thickness. Weight strikes us immediately as we are in flight where this property is paramount. Thus the solution hints at changing weight of ice to be measured, which is in some good proportion to thickness. In fact, going by integration, differential film of ice over a large area may be a finite number, measurable more easily than ice film thickness that can be in micro or even nano meters.

With this thought process concluding, we now think methods to measure weight. One of them is putting a sensor or probe that is installed at a sensitive location and is continuously vibrating due to piezo-electric effect. Even better, it is in resonant mode. With deposit of ice on probe, resonance will offset very sharply and this can be measured rather too easily. The **magnetostrictive effect used is of course more precise and advanced and hence is accepted as standard technology**

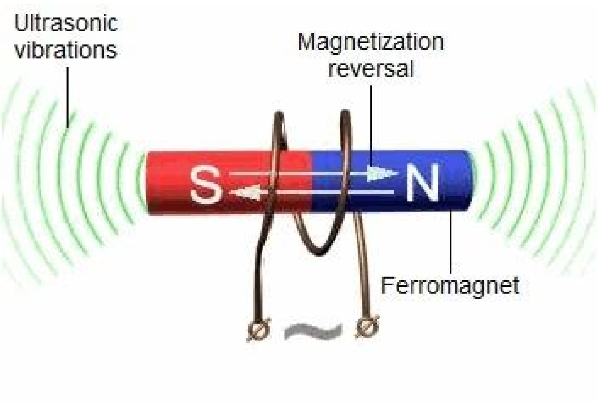
Related applications….

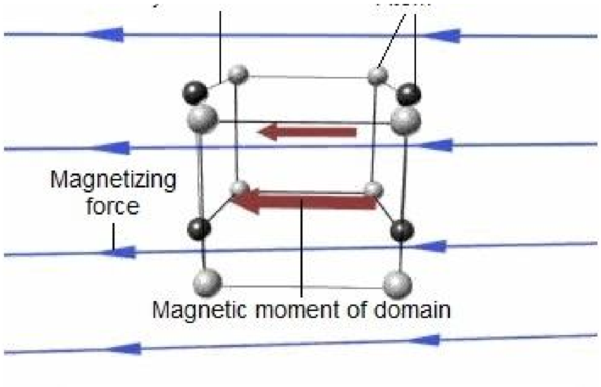


Microdosing Liquid

Biological specimens are given liquids using a micropipette.
Disadvantage: It is not easy to control the liquid dosage.
It is proposed that the liquid be exposed to ultrasonic vibration.
The vibrations force the liquid out of the pipette. A core of magnetostrictive material is used. The core transforms the energy of an alternating magnetic field into ultrasonic vibrations. The injection dosage is controlled by changing the vibration frequency and amplitude.

Magnetostrictive excitation of ultrasonic vibrations





Description

In polycrystal ferri- and ferromagnets, the displacement and rotation of the magnetic moments corresponding to the constituent domains accompany magnetization reversal. The displacement and rotation of the magnetic moments of domains change the polycrystal lattice energy state. Equilibrium distances between atoms change in the lattice. Polycrystal surface vibrations reveal this change.

The polycrystal surface vibrations are transferred to the surrounding medium in the form of elastic vibrations. This excites elastic vibrations of an ultrasonic frequency in the medium, if the magnetization reversal frequency corresponds to the ultrasonic range.

Advantages

1. The operating frequencies of excited vibrations are 8 to 100 kHz.

2. The operating amplitudes of the transducer surface displacement are up to 25 μm.

3. The vibration intensity in the operating medium may reach 0.01 $W/m^{2.}$

4. In transducer designing, acoustic resistances of the load and the transducer are matched in order to provide a maximal efficiency.

Effect Index

$$\eta = W_a/W$$

η – efficiency of the transducer

W_a – acoustic power at the transducer output, W

 – total power of the transducer, W

Limitations

η varies from 0 to 0.6.

Materials

For permendure EP 207, at a frequency of 22 kHz and the radiation surface of 300 mm, $\eta = 0.55$. For ferrite, at the frequency of 44 kHz and the radiation surface of 40 mm, $\eta = 0.6$.

Formula

$$\frac{\partial u}{\partial t} = \frac{\gamma SB(1 - \cos(kl))}{SZ_c \sin(kl) - Z_n \cos(kl)}$$

$$k = \frac{2\pi}{\lambda}$$

$\partial u/\partial t$ – speed of displacement of the operating surface of a ferromagnetic transducer, m/s

u – displacement of the operating surface of a ferromagnetic transducer (core), m

t – time, s

γ – magnetostrictive constant, $N/(m^2 \cdot T)$

S – section area of the operating surface of a ferromagnetic transducer (core), m^2

B – magnetic induction, T

k – wave coefficient, m^{-1}

l – transducer length, m

Z_c – acoustic resistance of the transducer (core) material, $Pa \cdot s/m_3$

Z_n – acoustic resistance of the load (medium receiving the vibrations) material, $Pa \cdot s/m_3$

π – constant = 3.14…

λ – wavelength of ultrasonic vibrations in a ferromagnetic transducer, m

Conditions

1. The ferromagnet must be placed in an alternating magnetic field.
2. The magnetic field induction must vary according to the harmonic law with a frequency corresponding to the ultrasonic vibration band.
3. The magnetic field induction must be sufficient to reverse the ferromagnet magnetization.

References

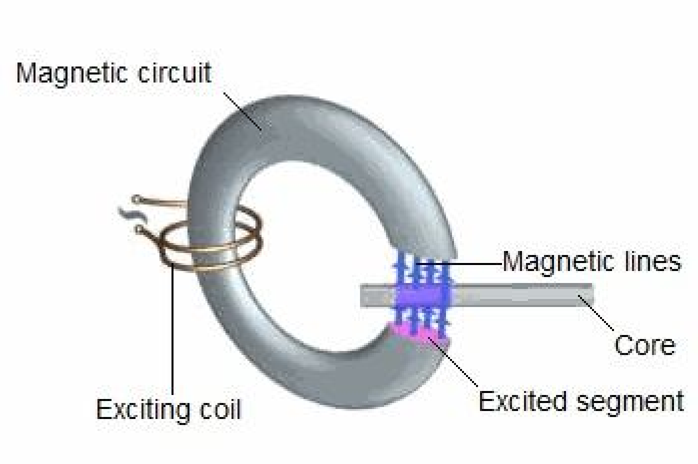
Agranat, B.A., ed. *Ultrasonic Technology*. Moscow: Metallurgia, 1974.

Burke, H. *Handbook of Magnetic Phenomena*. Van Nostrand Reinhold Company Inc., 1986.

Kikuchi, Y., ed. *Ultrasonic Transducers*. Tokyo: Corona Publishing Company, LTD, 1969.

Mason, Warren P., ed. *Physical Acoustics. Principle and Methods*. *Methods and devices.* Vol 1. Part A. New York: Academic Press, 1964.

Magnetostrictive transducer with elliptic section



Description

The magnetostrictive transducer is made of a core, an exciting coil, and a magnetic circuit. The magnetic circuit has an elliptic section. The circuit can rotate around the axis that runs through the center of the section parallel to the magnetic force lines.

As the circuit turns, the length of the excited segment of the core changes due to the elliptic section of the circuit. Different turning angles are chosen for pulses of different lengths. The length of the excited segment is proportional to the length of the excited pulse.
Example: Synchronizing radiation of dischargers
Example: Tube flexibility increase using elliptical shape
Example: Volume changing in chamber using elliptic hoops

Advantages

1. The magnetostrictive transducer with an elliptic section generates pulses of different lengths.
2. The transducer increases the pulse transducing efficiency.

Problem

The length of the excited segment of a core in a doughnut-shaped magnetostrictive transducer is constant. Such a transducer generates pulses of the same length. It is often necessary to produce pulses of different durations.

Solution

In order to efficiently obtain pulses of different lengths,
it is proposed to rotate a magnetic circuit with an elliptical section.