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ENGINE CONTROL - A NEW HIGH ACCURACY PRESSURE SENSOR

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ABSTRACT

Engine control applications need pressure transducers which have to provide very good accuracy, reliability, with low dimensions and weight, with severe environmental capabilities.

We describe here a new high accuracy pressure transducer, due to more than 20 years of CROUZET background, and built around a quartz vibrating beam.

This type of transducer, issued from the up-to-date design methods and tools, microelectronic integration capabilities, provide very high accuracy (better than 0,05 % full scale) stability (better than 0,015% full scale for 1 year) and reliability (MTBF predicted ≃ 200 000 hours).

INTRODUCTION

The Engine Transducer 55, subject of this presentation, is the results of more than 20 years of CROUZET background in the field of sensors, especially :

- pressure transducers for aeronautical applications,
- vibrating beam sensors,
- quartz technology,
- microelectronics technology.

Since 1967 CROUZET has produced over 30.000 transducers for installation in a wide range of applications and operating environments. The first transducers were installed in CROUZET Air Data Computer. These computers are installed in many of today's modern aircraft including the MIRAGE fighter aircraft, Alphajet, Jaguar, and the latest state of the art fighter, the Rafale. Transport aircraft installations include the Airbus series aircraft Boeing 747, Transall and Concorde, AEROSPATIALE Dolphin and Super Puma helicopters utilize CROUZET pressure transducers in a severe environment.

CROUZET has been working with turbine engine manufacturers -Turbomeca, Snecma, Microturbo) for over ten years. Pressure transducers have been supplied for engine testing where very high accuracy is demanded, and in turbine engine applications where very high operationnal reliability is required. CROUZET has also supplied Elecma, a manufacturer of Controls in France, with hybrid circuits for the regulation of the CFM 56-5 engine.

The ET 55, particularly developped for Engine Control, has to provide :

- high accuracy, stability
- high reliability
- severe environmental capabilities
- low dimensions
- low cost.

In the following paragraphs, we shall describe the principle of the measure, the design philosophy that CROUZET have been introduced in this development to achieve the targets above, and we shall conclude by the main results in term of accuracy and stability for this device.

DESIGN PHILOSOPHY

The Engine Control requirements can be met by several measurement techniques that are presently available and qualified by CROUZET.

- Servo force - balance sensors
- Membrane and strain gauge sensors
- Membrane and capacitance variance sensors
- Vibrating beam sensors.

Considering accuracy and volume requirements, the quartz vibrating beam principle is the best choice. This advantage is due to inherent accuracy and quality of a resonating system.

The following are the important characteristics contributing to sensor accuracy :

- successful operation in severe environment and output stability
- no moving mechanical parts (solid-state sensor)
- simplified mechanism and minimum number of parts
- no sensitive to the sensed medium

These previsions are made to ensure compliance with severe environmental conditions and to enhance reliability of the transducer :

- high temperature and stable materials are used to withstand the demanding transducer environment. The materials include : beryllium brass, quartz, stainless steel low carbon grade.

- thick layer hybrid technology is used for the electronics, which is hermetically encased.

- pre-aging of the mechanical parts at a greater temperature than the operating temperature.

- aging of the assembled transducer and control of its behavior for long time.

PRINCIPLE OF QUARTZ VIBRATING BEAM SENSORS

Introduction

The output signal of such a sensor is the frequency of an oscillator locked on a flexural vibration mode of a thin quartz beam.

The vibration frequency is a linear function of the longitudinal stress applied to the beam, which permits to realize a force sensor.

The physical quantities, which can be measured by this mean, are either :

- a pure force
- an acceleration, by adding a proof mass
- a gaz pressure, by adding a conversion device.

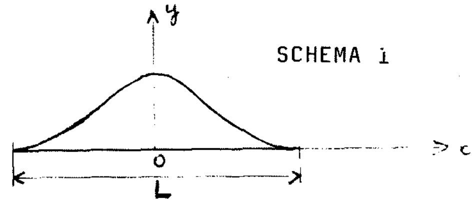
Flexural vibrations of a beam

For a beam fixed at both ends, the lowest frequency mode has the highest sensitivity force - frequency. With a longitudinal stress F = 0, the resonant shape of the beam average line is given by the following expression

$$y = Yo \left[\cos \alpha x + 0{,}133 \ \mathrm{ch}\, \alpha x \right] \cos \omega_0 t$$

with $\alpha L = 4{,}73$

SCHEMA 1



The resonant frequency $f_o = \frac{\omega_o}{2\pi}$ is given by the following formule, wich is precise if $e/L \ll 1$:

$$f_o = \frac{(4{,}73)^2}{2\pi} \frac{e}{L^2} \sqrt{\frac{E}{12p}}$$

L is the beam length, e the thickness in xy plane, l the width, E the young modules, p the density.

Sensitivity force - frequency

It can be shown that the evolution of frequency versus stress is given, with a very good approximation, by a root function :

$$f = f_o \sqrt{1 + \frac{F}{Fc}} \quad \text{if } |F| < Fc$$

The critical stress F_c is : $F_c \simeq \frac{4\pi^2}{L^2} EI$

where $I = \frac{le^3}{12}$, moment of inertia of a cross section

If $\left|\frac{F}{F_c}\right| \ll 1$, then : $f \simeq f_o \left(1 + \frac{F}{2F_c}\right)$

The relative sensitivity :

$$\frac{1}{f_o} \quad \frac{\partial f}{dF} = \frac{1}{2F_c}$$

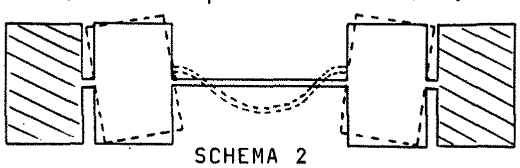
Quality factor of resonator

To minimize the frequency noise and the temperature drift, it is necessary to achieve a high quality factor for the resonator. The vibration damping is cause by several physical processes :

- internal damping due to viscosity and thermal conduction
- gaseous damping
- energy losses in the mounts.

Internal damping depends on the quality of quartz. Gaseous damping can be eliminated by reducing the inner pressure of the cavity.

As for energy losses in the mounts, they can be highly attenuated by using a decoupling means. The mechanical decoupling of the resonator is obtained by inertia effect by inserting between the beam and the supports rigid masses which may move, by means of flexible articulations, in the vibration plane of the beam.



SCHEMA 2

The dimensions of masses are judiciously defined, in order to cancel out on each articulation the resultant of the support reaction; a small residual torque continues to exist because of the non zero angular stiffness of the articulation.

The quality factors currently achieved are in the order of 100.000.

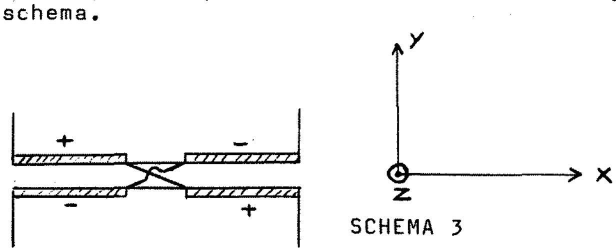
This type of decoupled resonator has been patented by CROUZET and ONERA (1).

Piezoelectric excitation

The interest of quartz, besides its stability and low temperature coefficient of its elastic constants, is to implement easily the excitation and detection of vibration, by using the piezoelectric effect.

The resonators are machined in a Z cut quartz and the shape of the electrodes depends on the beam orientation in the XY plane.

For example, if the beam is aligned along X axis, it is possible to use the following schema.



SCHEMA 3

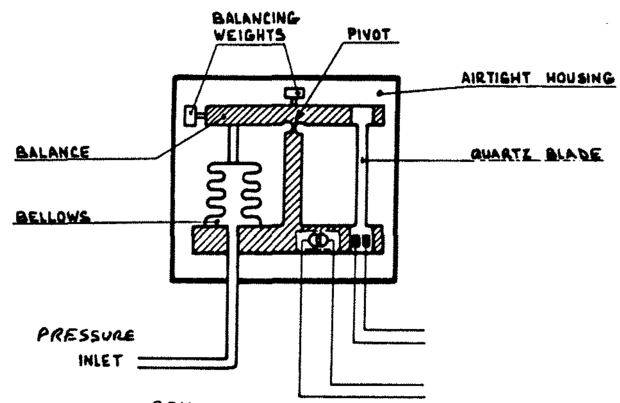
X, Y, Z are the crystallographic axes.

The two pairs of electrodes are cross-connected; the bending movement in the XY plane is then produced by means of opposite shearing stresses.

PRESSURE TRANSDUCER DESCRIPTION

Mechanical part

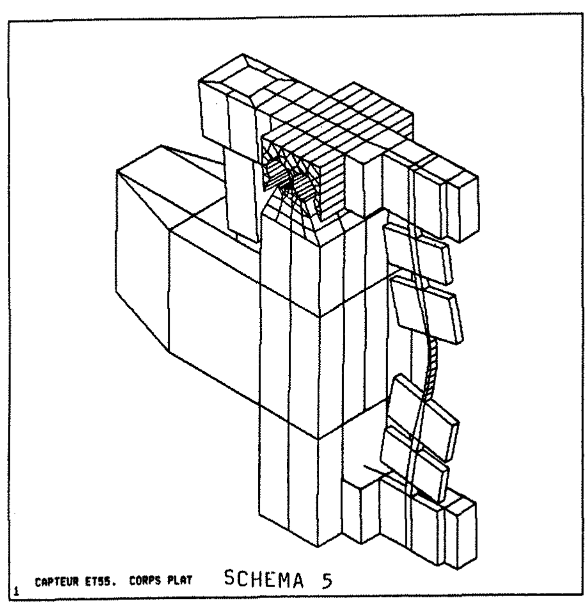
Sensor type 55 features a quartz vibrating beam. The pressure to be measured is converted into a force through a bellows. This force is applied to a resonator whose frequency varies in function of the applied mechanical stress.



SCHEMA 4

Mechanical Unit Schematic Diagram

The mechanical part is designed to minimize the effects of mechanical stress resulting from shock, vibration and acceleration. A finite element method of simulation is used to identify a pressure oscillator operating frequency range which avoids any sensitivity to unwanted resonance frequencies caused by external stimulus.



SCHEMA 5

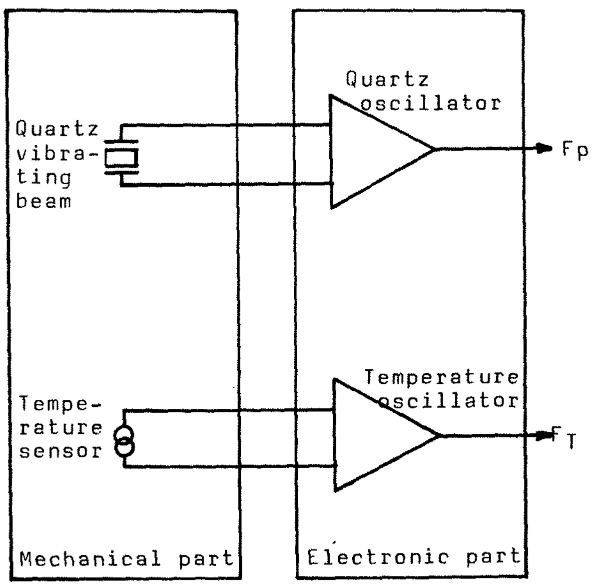
Static balancing is performed on the active components of the sensor such as the bellows, arm and the resonator.

Electronic part

Principle

The electronic part of the sensor has two functions :

- a quartz oscillator, built around the quartz beam, and which performs a frequency output Fp
- a temperature oscillator, built around an AD 590 Temperature sensor, and which delivers a frequency output F_T related to the mechanical part temperature.



The actual pressure can be then computed from both frequencies Fp et F_T by using a modelisation model. This model is calculated by CROUZET with high performance calibration bench (primary pressure standard).

Quartz oscillator

The quartz oscillator is composed of 3 parts :

- the oscillator itself
- the amplitude regulation circuit
- the output circuit.

The oscillator itself is built around a high bandwidth-op. amp. The principle is a bridge oscillator, which offers high stability.

One side of the bridge is the quartz beam, the other one is used as a filter in order to avoid parasitic oscillations (for example overtone oscillations).

The amplitude regulation circuit is necessary to avoid parasitic changes in the quartz vibrating frequency with the excitation power. This circuit is mainly composed of an amplitude detector and a regulator which as an action on an adjustable resistor placed in one side of the bridge.

The output circuit converts the sine wave signal into square wave signal, and provides the power necessary to drive the computing device, for both Fp and F_T. The point with those circuits is to obtain short transition times with a low gitter.

Temperature oscillator

This oscillator performs temperature information, which is used to correct the effect of temperature on the quartz beam, in order to achieve the expected performances.

The temperature sensor AD 590 gives a current output (1 µAmp per celsius degree).

The temperature oscillator is basically a current into frequency converter.

TECHNICAL REALISATION OF THE ELECTRONIC PART

In order to reduce the volume of the electronic part, it was chosen to use both hybrid thick film technology and ASIC (Application specific integrated circuit) technology.

The hybrid thick film technology has been successfully used by CROUZET company for more than 10 years, for space, aeronautic and civil applications. CROUZET has his own design, development and production means, for both internal and external customers. The main environment performances of the devices CROUZET produces are :

- temperature : - 55°C to + 125°C
- shocks : 1500 g - 0,5 ms
- accelerations : 10 000 g
- vibrations : 20 Hz to 20 kHz at 20 g

In the case of the ET 55 sensor, the size of the whole electronic is 44 x 14 mm (1.73 x 0.55").

Almost all the active parts of the electronic (that is to say more than 8 operationnal amplifiers and comparators) are located in a single ASIC device. A Special attention is paid by CROUZET to develop this linear high performance device in collaboration with the ASIC provider. This type of device offers good resistor matching performances (1%), and, on the same die, both high speed and precision amplifiers. The device is organized by the customer in macrocells which are related on the customer device by a metallic top layer.

This allows to obtain performances such as :

- offset voltage : 0,5 mV
- offset drift : 4 µV/°C
- large signal voltage gain : 80 dB
- input resistance : 5 M
- gain bandwidth product : 20 MHz

The die size is 189 x 123 mils with 44 bonding pads.

Features

This device is designed to perform the following general features :

- accuracy : typical 5.10^{-4} including non linearity, repeatibility, hysteresis, for the whole temperature range
- pressure range : 110 kPa to 4000 kPa
- temperature range : - 55°C to + 125°C
- overall dimensions (inches) : 2.6 x 1.9 x 0.69 (low pressure)
  2.6 x 1.9 x 0.53 (high pressure)
- power : 0; + 15 V
  typical consumption $<$ 25 mA
- weight : 0.5 pound

CONCLUSION

We can conclude this presentation by some data which are deduced from qualification tests of this type of sensor.

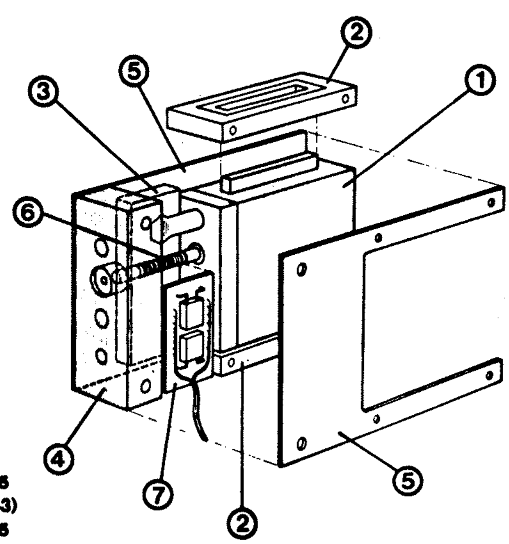
We have obtained very good repeatability results from short-term stability control. Repeatability is generally better than . 001 % full scale (FS).

The long-term stability, obtained in storage conditions during 2,5 years, is better than .01 % FS.

The stability after combined Pressure (more than 275.000 Pressure cycles) an Temperature cycles - 40°C to + 90°C is better than .013 % F.S.

SCHEMA 6 : **ET55 overall exploded view**

① **Transducer Unit**
② **Shock/Vibration mount**
③ **Hybrid Electronic Unit**
④ **Mechanical and Pressure Interface**
⑤ **Packaging**
⑥ **Internal Pressure supply Tube**
⑦ **Interface Circuitry and Wire (with connector)**



Overall dimensions : High Pressure 66x48x13,5 (2.6x1.9x0.53)
Low Pressure 66x48x17,5 (2.6x1.9x0.69)

All these data show that both accuracy ($<$ .05%% FS) and stability ($<$ .015 % for one year in operational conditions) are full compliance facing Engine Control requirements.

No return because of drift or total failure, from more than 600 Pressure Transducers in operating conditions confirms the high reliability which is predicted (MTBF = 200 000 hours).

In conclusion, we think that the 55 Pressure Transducer performs good caracteristics to Engine Control application, due to low dimension, high accuracy, stability and reliability.

(1) French patent n° 84.185.87 (04/12/1984)
Inventors : H. FIMA -CROUZET S.A.
D. JANIAUD - ONERA