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ACTIVE STABILIZATION OF BANDPASS FILTER WITH MULTILAYER PIEZOELECTRIC ACTUATORS

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ABSTRACT

The applications of smart materials and structures have grown substantially in aerospace industries. With smart structures and materials, performance has the potential to improve and extend the capability of a device. As a first experience in this field, EMS has investigated the integration of multilayer piezoelectric actuators into an RF bandpass filter to compensate for the frequency shift induced by thermal distortion of the resonator tuning posts. The purpose of a Bandpass Filter is to separate frequencies in a communications signal. This type of filter lets a certain range of frequencies pass through, from the input port to the output port, while frequencies below and above the limits are rejected. A bandpass filter must keep its stability in temperature. A variation in temperature induces a frequency shift of the passband. In this project, EMS Technologies and Sensor Technology teamed for a collaborative work. Piezoelectric actuators have been developed and manufactured by Sensor in order to achieve the requirements specified by EMS. A breadboard was adapted to embed the piezoelectrics. A test setup was prepared and the breadboard was tuned and tested over a wide range of temperature. Although the previous design was relatively stable, there was still room for improvement. Over a temperature range of 50°C (-10 to 40°C), the frequency shift was 0.0097% (or 0.150 MHz). However, with the controlled piezoelectric actuators, the frequency shift is three times smaller, down to 0.0033 % (or 0.050 MHz). A trade-off in terms of electrical performance in temperature, mass, integration complexity, risk, cost, etc shows that in future applications, active control of bandpass filter with piezoelectrics should be considered. Additional work is required for flight qualification of the piezoelectrics and to reduce the weight and cost of the driving electronics.

1. INTRODUCTION

There is a major trend in the aerospace industry to use active control. EMS Technologies is interested in developing products where active control is employed. For this project, it is proposed to apply the control technology to a Bandpass Filter.

A Bandpass Filter is a critical component that must keep its stability in temperature. A variation in temperature induces a frequency shift of the passband. This frequency shift must be controlled within stringent constraints. Presently, bandpass filters are only tuned on ground prior to launch. However, this kind of tuning is not sufficient since, once in space, their shape might be considerably affected by the high temperature gradient they face. Therefore, heavy and complex thermal hardware is required to minimize this gradient. One of the possible ways to have a thermally stable Bandpass Filter is to use piezoelectric actuators.

In this project, EMS Technologies and Sensor Technology Limited from Collingwood, Ontario, teamed for a collaborative work. EMS procured the piezoelectrics and associated hardware from Sensor. Piezoelectric actuators have been developed and manufactured by Sensor in order to achieve the requirements.

In this study, a breadboard was adapted to include linear piezoelectrics. A test setup was prepared and the breadboard was tuned and tested over a wide range of temperatures. The original passive design is already very stable. Over a temperature range of 50°C (-10 to 40°C), the frequency shift is 0.0097% (or 0.150 MHz). However, with the controlled piezoelectric actuators, the frequency shift is three times smaller to 0.0033 % (or 0.050 MHz).

A trade-off in terms of electrical performance in temperature, mass, integration complexity, risk, cost, etc. shows that in future applications, active control of Bandpass Filter with piezoelectric actuators should be taken into account, especially for precise application or very high frequency.

2. BANDPASS FILTER DESCRIPTION

2.1. Bandpass Filter Principle

The purpose of a Bandpass Filter is to separate frequencies in a communications signal. One of the most common types of Bandpass Filter is the reflective type such as those of AceS and Inmarsat-4 [3]. This type of filter lets a certain range of frequencies pass through, from the input port to the output port, while frequencies below and above the limits defined are reflected (or “bounced”) back to the source of the signal.

The way many types of filter achieve this frequency selection is by resonance. The filter is made up of a cascade of resonators, a resonator being a structure which has the right size to resonate at one special frequency. Resonance consists of input electromagnetic waves bouncing back and forth and building up power, which may then be extracted at a separate output port. A set of resonators acting together can allow a range of frequencies to resonate and pass through to the output. The performance of a Bandpass Filter can be expressed with several parameters such as return loss over the passband, maximum gain variation, frequency shifts, etc. A temperature variation will induce a frequency shift.

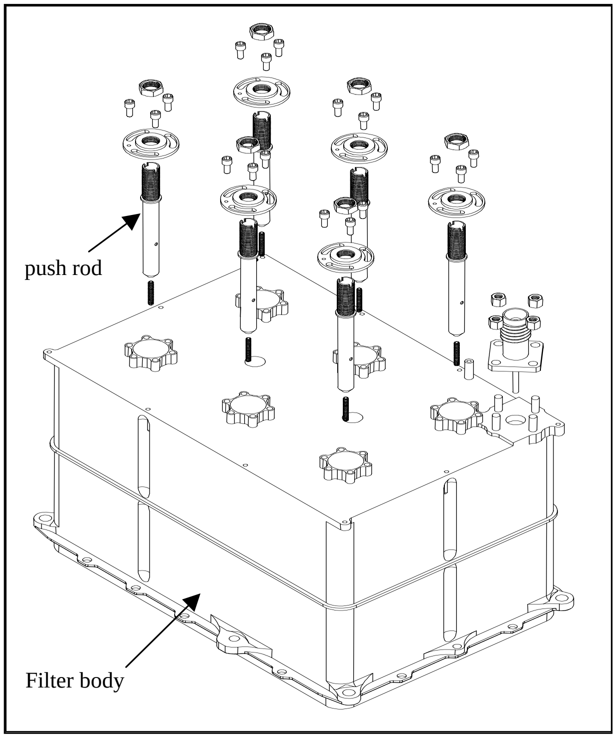

Figure 1 Exploded view of Inmarsat-4 Transmit Bandpass Filter

The most sensitive parameter in a Bandpass filter is the size of the resonator and the most sensitive part of the resonator being the post, in both length and diameter. Post length is the usual parameter chosen to be adjustable (by screw extension or bellows action) to allow accurate tuning of the resonant frequency. The push rod shown in Figure 1 acts as the tuning screw to set the post height as required. Resonant frequency is sensitive to post length changes of 2 microns, even at lower microwave frequencies such as 1500 MHz.

2.2. Breadboard Bandpass Filter

A breadboard filter was built to demonstrate that the piezoelectric actuators could compensate for the frequency shift. Figure 2 shows the breadboard design with the actuators out of the resonator cavities. The piezoelectric actuators replaced the original push rods.

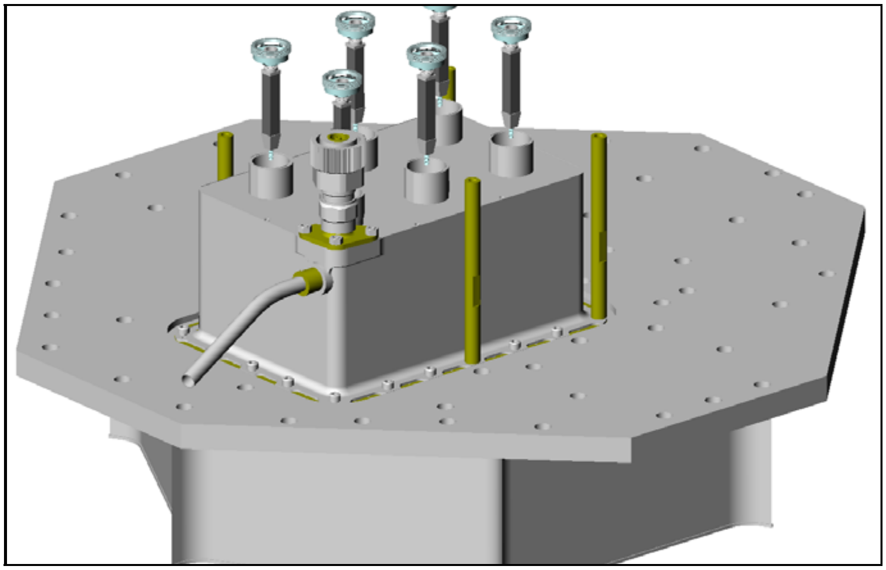

Figure 2 Breadboard Bandpass Filter with Piezoelectrics (Exploded View)

3. PIEZOELECTRIC ACTUATOR SELECTION

3.1. Piezoelectric Actuator Design Criteria

Based on AceS-I, AcesS-II and Inmarsat-4 heritage some requirements have been established in order to define the specification for Sensor Technology to manufacture the piezoelectrics. Furthermore, some requirements specific to the Breadboard were derived from calculation. The piezoelectrics design criteria are given below:

- The actuator itself should ideally fit in a 7.6mm diameter by 41mm long cylindrical envelope.
- The temperature ranges for Inmarsat-4 is for the transmit and receive Bandpass filters are the following:

  Qualification, operating: -13 ºC to 91 ºC.

- The displacement required was calculated taking into account the material and temperature range. The calculated value is between 10 to 30 micrometers depending on the coefficient of thermal expansion (CTE) of the actuator itself.
- The maximum push and pull forces required by the actuator is about 5 lbs.

A large variety of piezoelectric material and shape exist on the market and we had to select the best-suited configuration for the current application. A review of Sensor Technology's standard products was conducted.

3.2. Piezoelectric Actuator Final Design

After reviewing the requirements with Sensor Technology, a final design was defined. This design is shown in Figure 3.

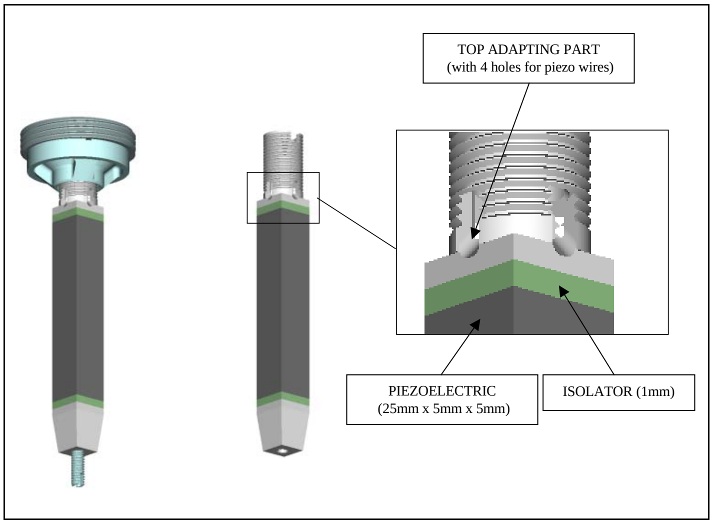

Figure 3 Piezo-Actuator Assembly

The final design is a stack actuator of 100 layers of SensorTech BM532, a Navy type V equivalent ceramic. This material was chosen because of its high d_{33} constant (630 pC/N). At the two ends of the stack, there are two adapting parts. These parts were designed to accommodate 2 existing parts that join the pushrod to the body of the Filter. Therefore, the design of the piezoelectric actuator is the simplest so that it could be easily integrated into the Bandpass Filter.

A 1-mm-polymer isolator was necessary between the stack and the adapting part. These isolators are "non-effective" components that must be added to the total length of the piezoelectric actuator assembly. The length of the stack had to be long enough to generate the required displacement and also short enough to fit in the envelope.

Displacement VS Voltage curves were plotted for each actuator by Sensor. A typical curve is shown in Figure 4. It can be seen from the figure below that the piezoelectric actuator shows some hysteresis.

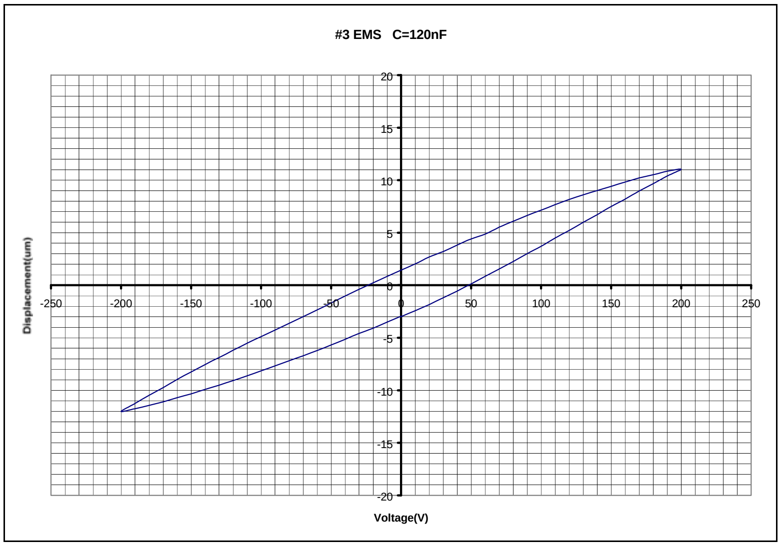

Figure 4 Typical Displacement VS Voltage Curve

Figure 5 shows a picture of the final design compared with the baseline pushrod used in the passive filter.

Figure 5 Piezoelectric beside a reference Pushrod and a Nickel

4. PIEZOELECTRIC CONTROL PHILOSOPHY

The goal of the control loop was to control the post height so that the Bandpass Filter performances are kept to an acceptable range of RF performance. The strategy adopted to control the filter performance in this study was to build a table that relates the temperature of the filter to the applied voltage during ground testing. In flight, the control program will interpolate in the table the voltage needed to keep the filter performance at its best. This philosophy is the simplest control loop that can be done.

The main advantage is the use of thermocouples as sensing devices. Those are a well-known and proven technology in space applications. However, it needs many hours of ground testing to build the table. This control contains no feedback on the change of dimension since the exact position of the bellows is not known and as shown in Figure 6.

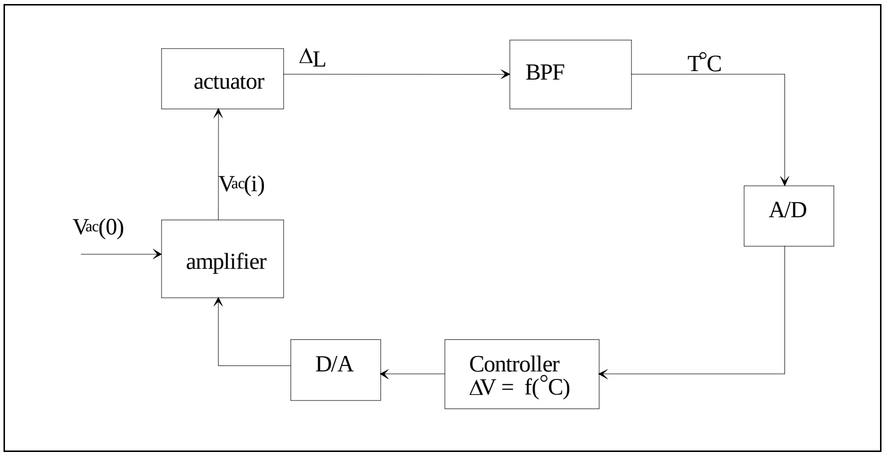

Figure 6 Temperature based control block diagram

5. TEST RESULTS AND DISCUSSION

5.1. BPF Characterisation

In the first set of tests, the goal was to characterise the BPF performance in temperature. The first test was done to characterise the BPF with the baseline pushrods. Looking at Table 1, one can see the frequency shift happening when the BPF is subjected to temperature change from its initial room temperature. In fact, the frequency shift is negative when the BPF is heated and the shift becomes positive when the BPF is cooled. Table 1 also quantifies in terms of MHz and percentage the center frequency shift observed during the test. At 90°C, the shift reached its maximum of –0.02%. This test also allowed the determination of an effective CTE for the BPF with pushrods. The effective CTE can be calculated using the following equation:

$$CTE_{eff} = \Delta f / (\Delta T\ f_{cen}) \qquad (1)$$

where Δf is the frequency shift, ΔT is the temperature gradient from initial room temperature and f_{cen} is the band center frequency. Table 2 gives the calculated effective CTE for the BPF with pushrods. As it can be seen, even if the bellows is made of aluminum (CTE = 23.6e-6 /°C), the effective CTE of the assembly pushrods/bellows is much lower.

The second test was a repetition of first one, but with the pushrods replaced by the piezoelectric actuators. No voltage was applied to the actuators to have a base of comparison between the pushrods option and between the control option. Moreover, this test was helpful in determining the effective CTE of the actuator/bellows assembly. Thus, by using equation (1), it was possible to derive an approximate CTE for the piezoelectric stack. The CTE of the stack actuator assembly was approximated to be in the range of 3 to 4 ppm/°C.

Table 1 Test Results Summary

	Fcen (MHz)	Delta Fcen (MHz)	Delta Fcen (%)	Overall Fcen (MHz)	Overall Fcen (%)	Tavg
BPF Performance Test with pushrod in temperature	1541,750	N/A	N/A	N/A	N/A	21,4
	1541,675	-0,075	-0,0049	N/A	N/A	41,0
	1541,450	-0,300	-0,0195	N/A	N/A	91,6
	1541,900	0,150	0,0097	N/A	N/A	-32,2
	1541,825	0,075	0,0049	**0,150**	**0,0097**	-11,3
BPF Performance Test with piezo in temperature (No Voltage)	1531,925	N/A	N/A	N/A	N/A	21,6
	1531,900	-0,025	-0,0016	N/A	N/A	39,2
	1531,650	-0,275	-0,0180	N/A	N/A	90,8
	1532,325	0,400	0,0261	N/A	N/A	-29,8
	1532,200	0,275	0,0180	**0,300**	**0,0196**	-10,4
BPF Performance Test with piezo in temperature (Manual Voltage)	1532,050	N/A	N/A	N/A	N/A	22,2
	1532,025	-0,025	-0,0016	N/A	N/A	-10,4
	1532,075	0,050	0,0033	**0,075**	**0,0049**	39,7
BPF Performance Test with piezo in temperature (Automatic Voltage)	1532,050	N/A	N/A	N/A	N/A	21,6
	1532,000	-0,050	-0,0033	N/A	N/A	-10,0
	1532,050	0,000	0,0000	**0,050**	**0,0033**	39,9

Notes: 1) Delta Fcen (MHz and %) are given with respect to ambient temperature
2) Overall Fcen (MHz and %) are given over the temperature range (-10 to 40 deg C)
3) Tavg is the temperature average of the 11 thermocouples on the Bandpass Filter

Table 2 BPF effective CTE

Bandpass Filter	CTE from 20 to 90°C [/°C]	CTE from 20 to -30°C [/°C]
with pushrods	2.758E-06	1.811E-06
with actuators –no control	3.683E-06	3.604E-06

Again, looking at Table 1, we can see that the maximum and minimum frequencies are shifted up or down depending on the temperature. Table 1 gives the center frequency shift for various temperature gradients. If we compare the frequency shift in percentage between the pushrods and the actuators, we can see that the shift is more important for the actuators. This is due to the fact that the piezoelectric stack has a higher CTE than the original pushrod and, Table 2 confirms this statement.

Another main difference between the BPF with pushrods and the BPF with actuators is the frequency band at which the filter is operating and its minimum return loss. This difference is attributed to the tuning of the filter when using the actuators. It was not possible to get the same frequency band because the actuator assembly was longer that the pushrod. This means that it was impossible to adjust the bellows to the same height as it was with the pushrods. Moreover, it was desirable that the actuators be always in compression during temperature cycling to prevent tensile loads in the stack. Consequently, the actuators had to penetrate more deeply inside the bellows to make sure that the actuators are always pushing against the bellows and not pulling them. This, again, changed the bellows height from its original position and consequently shifting the frequency band.

5.2. <u>BPF Active Control</u>

The second set of tests was done to assess the feasibility of controlling the BPF performance with piezoelectric actuator stacks. As explained in section 4, the control philosophy adopted is a relationship between the temperature of the BPF and the voltage needed to keep its performance optimal. This test was performed to find this relationship and to define the temperature limits at which the actuator can correct the thermal expansion of the bellows. The results of the test are given in Figure 7. The voltages read on Figure 7 are the voltages at the input of the power amplifier. To get the voltage at the piezo-actuator, the input voltage has to be multiplied by the gain of the power amplifier which is 15. The figure illustrates clearly the hysteresis phenomena observed in piezoelectric materials [4]. It tells us that the actuator can only control the bellows thermal expansion from -13°C to 45°C. This is far below our requirements of 90°C operating temperature.

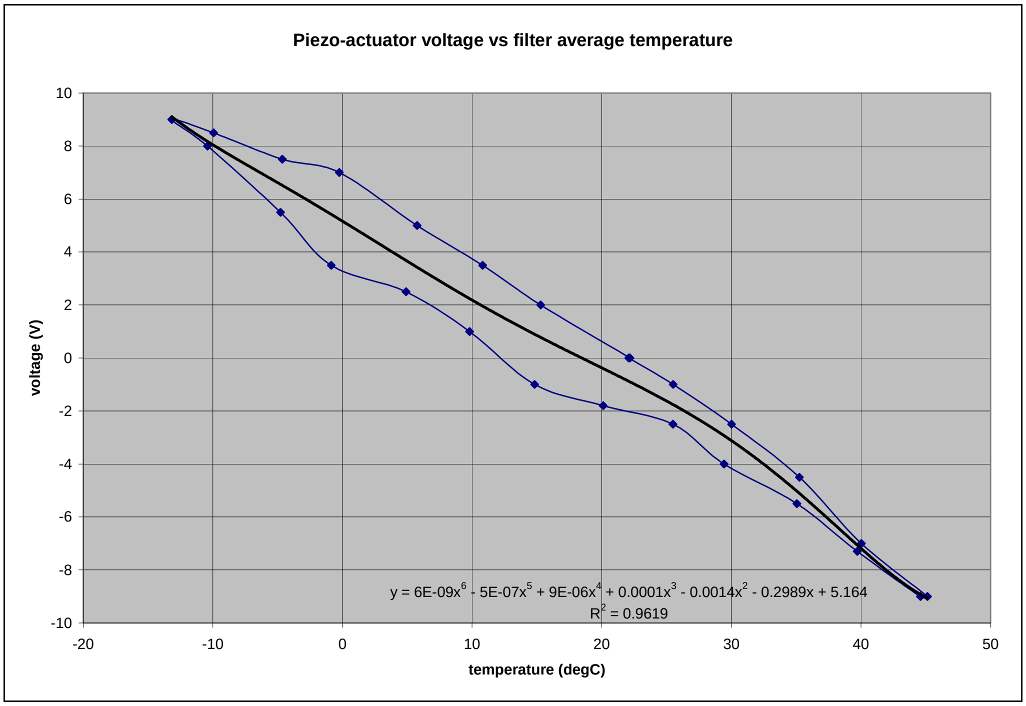

Figure 7 Piezoelectric Actuator Voltage / BPF Average Temperature Relationship

The first reason to explain this deviation is that the power amplifier was only giving a maximum output voltage of 140V instead of the 200V assumed in the definition of the requirements. In other words, the maximum displacement of the actuator was reduced by 30%. In Section 3.1, we were asking for a minimum displacement of 10 μm for a temperature gradient of 70°C. With the reduction in output voltage, the maximum gradient should be going down to 49°C. This means that the maximum temperature, at which control is possible, is now 69°C. Possible explanations for this difference may include:

- Hysteresis of the piezoceramics
- Error on estimation of the piezoelectric actuator CTE
- The force needed to actuate the bellows is higher than predicted, thus reducing the displacement of the actuator

The goal of the test was also to find a relationship between the voltage needed and the temperature measured. The relationship can be expressed by a polynomial that best fits the curve shown on Figure 7. The use of a polynomial will minimize the error that would be generated by the hysteresis. The following equation gives the relationship needed:

$$V = 6E\text{-}09\ T^6 - 5E\text{-}07\ T^5 + 9E\text{-}06\ T^4 + 0.0001\ T^3 - 0.0014\ T^2 - 0.2989\ T + 5.164 \quad (2)$$

The BPF performance obtained during the test are excellent in the temperature span where the actuators are efficient as shown in Table 1. Finally, the last task was to program equation (2) into the control software and measure the RF performance over temperature. As we can see in Table 1 and Figure 8, the center frequency shift is the smallest of all tests performed on the BPF. In fact, the active control loop is 3 times better than the baseline pushrod option and even better than the manual control test.

6. CONCLUSION

The Bandpass Filter performance obtained during the tests with piezoelectric actuators is very stable in the temperature range where the actuators are efficient. With the piezoelectric actuators, the frequency shift is three times smaller than with current design with pushrods. Even though this temperature range is reduced with respect to the initial requirement, on a technical point of view, it would be worthwhile to follow on the work on the implementation of piezoelectrics in BPFs.

More work will have to be accomplished on the piezoelectrics to qualify for flight production. Furthermore, some effort will have to be spent in order to design and manufacture lightweight and low-cost electronics to drive the actuators.

EMS will perform some follow-on work under Active Stabilization of Bandpass Filter, Phase II. This phase will consist in investigating the ways to implement the Bandpass Filter in space application. Therefore, the main activities conducted in the project will be to revisit the Bandpass Filter design, investigating the miniaturization of hardware (power supply, control units), software coding and piezoelectric integration. Component testing in a relevant environment (thermal and vacuum) testing will also be conducted. Some fatigue tests will be performed on the piezoelectrics to have a better assessment of their property losses in time. In parallel to these activities, the ground tuning procedure will be reviewed in order to automate the process, enabling a significant reduction of the tuning duration.

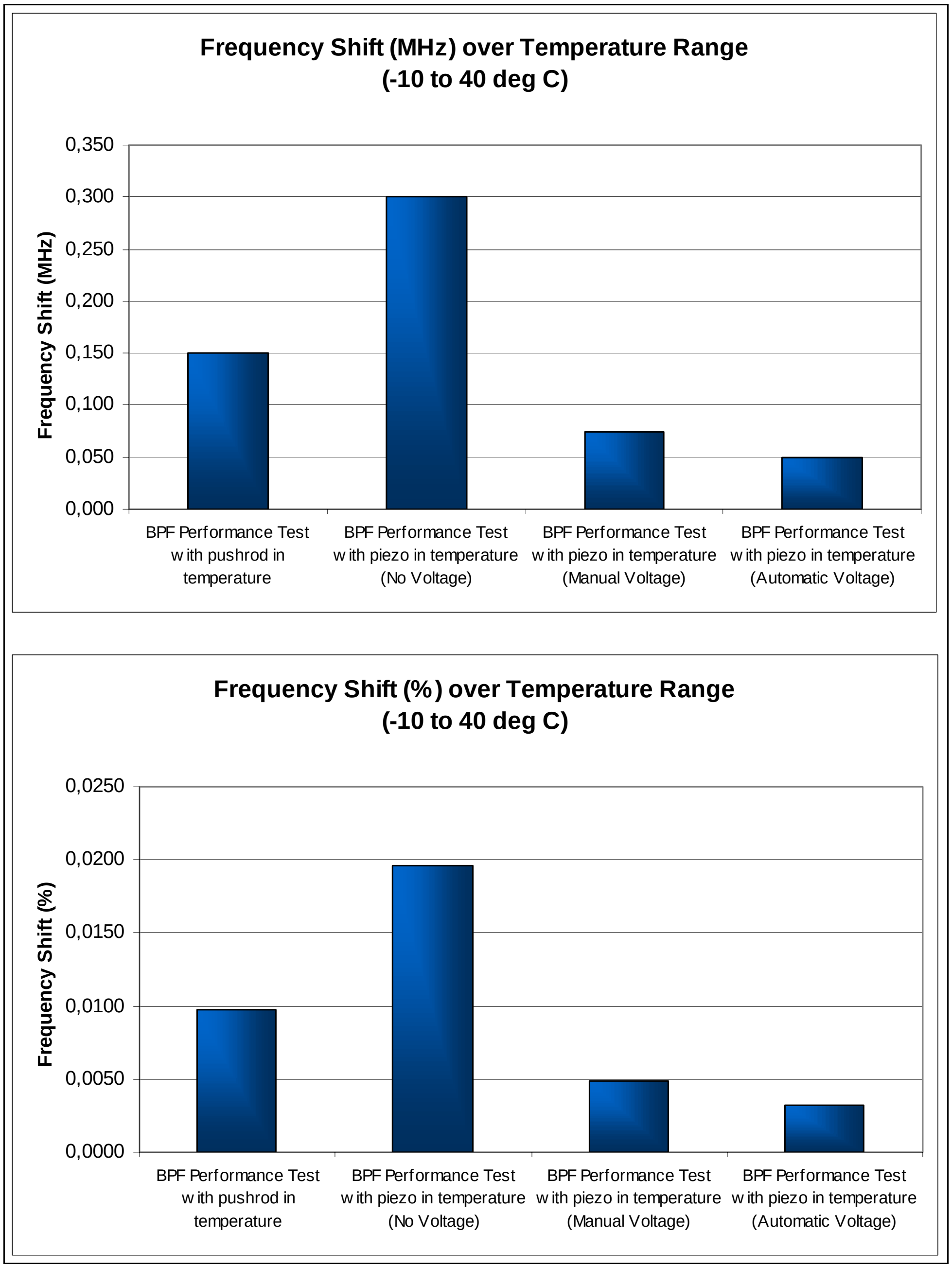

Figure 8 Frequency Shift (MHz and %) over Temperature

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8. AKNOWLEGMENT

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