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Smart Materials Used in Frequency-Selective Passive Sensors

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A low-cost passive system that senses and records the maximum pressure excursion in a specific frequency range was recently designed and tested. The system uses microballoons mixed into grease as a pressure sensing smart material. The frequency selection was achieved by using a fluidic filter. The fundamentals behind the design, the design details, and the launch performance are presented. The system was designed, built, and deployed to passively record the maximum gas pressure in a selected frequency range at a number of positions on the pad during a Titan IV launch. The design fundamentals and data obtained during a recent launch are presented.

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PREFACE

We are most grateful to G. C. Panos for his assistance in physically recovering and processing the microballoon-tagged material, and to M. T. Quinn, R. L. Ruiz, G. C. Panos, and R. C. Savedra for helping to assemble the sensors.

CONTENTS

FIGURES

INTRODUCTION

While looking ahead to regular use of the new higher-thrust versions of the Titan vehicle, low-frequency pressure was flagged as a concern impacting the structural integrity of the launch pad. Initial calculations predicted pressures as high as 150 psig on launch pad structures close to the vehicle. Among the activities to address this concern was the actual measurement of pad pressures during the first west coast Titan IV launch. In addition to an active measurement system covering a limited portion of the pad, a Microballoon-Tagged Material (MTM) technology was developed to back up the active system and provide additional coverage on other parts of the pad that were inaccessible to active sensor installation. The MTM is a "smart" material that can passively measure and record maximum pressure.[1] In its original application, the MTM was used in a benign environment to record quasi-static maximum pressures in a fluid.[2] In this new application, the MTM sensor system was hardened to survive the severe pad environment during launch, and a fluidic low-pass filter was employed to shield the MTM from high frequencies.

MICROBALLOON-TAGGED MATERIAL

Microballoons are small hollow glass spheres with diameters in the range of ~1 µm to 100 µm. The fundamental property permitting the use of microballoons in passive pressure sensors is that in any bulk sample of microballoons, the individual microballoons possess a random mixture of rupture strengths, varying over a very large pressure range. The basic technique implementing the microballoons as passive pressure sensors is illustrated in the sequence of Fig. 1. When the microballoons are mixed into a fluid vehicle, such as a grease, the resulting MTM is both a pressure sensor and a pressure recording device. When the MTM experiences a pressure excursion during use, microballoons possessing a rupture strength below that of the pressure excursion will break. The MTM is recovered, placed on an acoustic emission transducer, and is repressurized slowly. No acoustic events will occur until the pressure exceeds the past maximum pressure and the stronger microballoons begin to break. Thus, the onset of acoustic events indicates the past maximum pressure. Figure 2 shows typical acoustic emission data from samples of 3M C16/250 microballoons mixed into Dow Corning Molykote® 55 grease. If not previously pressurized, the acoustic events begin at about 18 psig, whereas the previously pressurized sample begins to yield events at 40 psig, in agreement with the prior maximum pressure.

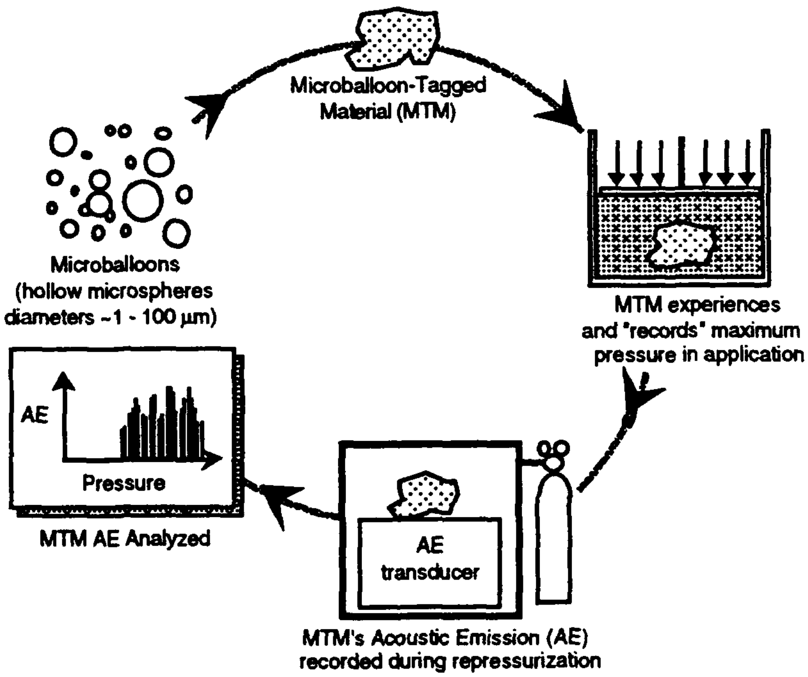

Figure 1. Basic procedure for MTM pressure measurement. MTM consists of microballoons mixed into a fluid vehicle, e.g., grease. The MTM experiences pressure *in situ*. The MTM is recovered, placed on an acoustic emission transducer, and repressurized. The onset of acoustic emission indicates the previous pressure maximum.

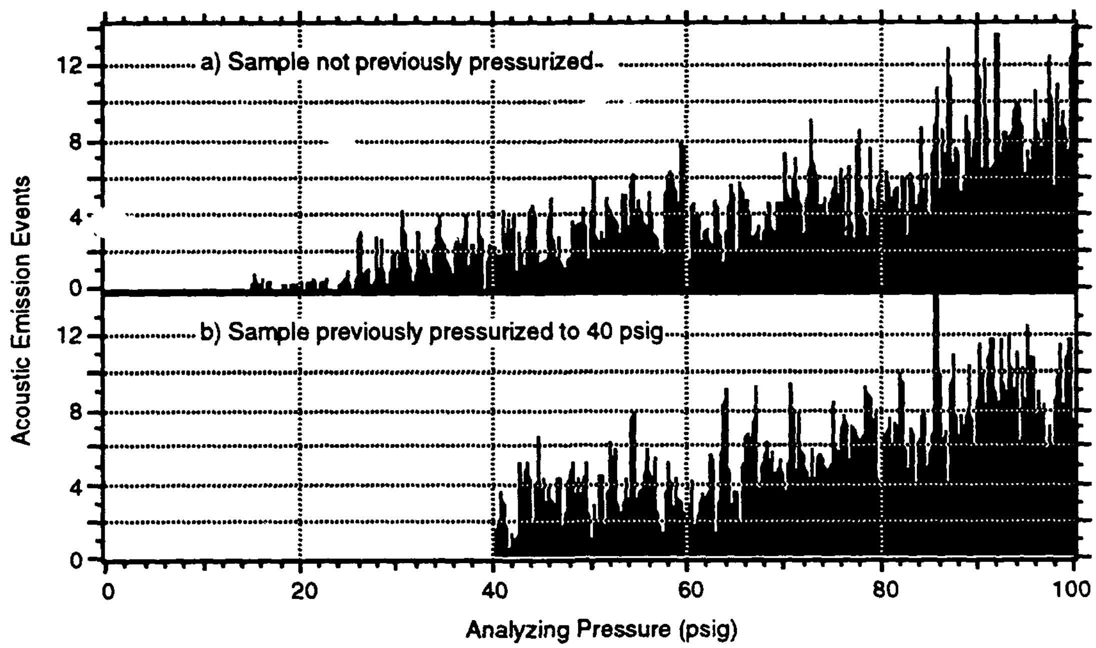

Figure 2. Two MTM samples with different pressure histories were placed on AE transducers and pressurized slowly. a) A virgin sample of MTM starts to generate acoustic emission events at ~18 psig. b) A sample previously pressurized to 40 psig does not emit sound on repressurization until 40 psig is exceeded.

The rupture of individual microballoons represents discrete events; thus, the pressure measurement by MTM is not a true continuous measurement. However, the population of balloons rupturing above 20 psig is high, as can be seen in Fig. 2a. Therefore, the measurement is essentially continuous for all practical purposes above 20 psig. Below 20 psig continuous measurements cannot be made since the population of microballoon rupture events becomes sparse.

In forming the MTM, the microballoons are suspended in a medium to transmit the pressure to the individual microballoons and to facilitate their handling. Experiments with various suspension media for the microballoons indicated that light oils facilitated the maximum sensitivity to the microballoon-rupture signal. However, the very low specific gravity of the microballoons themselves resulted in their segregating to the top of the MTM. This results in non-hydrostatic forces on the microballoons during pressurization, leading to potential erroneous pressure readings. We chose, on the basis of prior experience, Dow Corning Molykote® 55 grease for a suspension medium. It exhibits a yield stress, thus minimizing the tendency to segregate.

FLUIDIC LOW-PASS FILTER

High frequency pressures are present during launch. However, only low frequency pressure changes, which could affect structures, were of interest. Laboratory experiments with shock-tube pressure pulses showed that MTM can accurately record peak pressures in pulses whose widths correspond to frequencies up to a kilohertz and peak pressures in the 50 to 150 psig range. (Higher pressure ranges were not investigated.) Therefore, a filter was required that could shield the MTM from pressure variations of frequencies above about 1 Hz. A fluidic low-pass filter was designed and implemented.

The model for the low-pass filter is based on fluidics principles and suggested itself from the exponential depressurization behavior of a pressurized vessel with a small leak. The filter consists of a sealed pressure reservoir connected to the external environment by a small inlet hole as schematically shown in Fig. 3. The functional form of the pressure decay in the above model has an electrical analog in the 1/RC behavior of an R-C low-pass filter. In this case, the reservoir is the capacitor, the inlet holes (restrictions) are resistors, and the pressure is the voltage.

The volume of the filter was fixed by practical size constraints imposed by the launch pad facilities. Because of the difficulty and uncertainties involved with the numerical analysis of such a system, we experimentally determined the size and number of holes required to give the desired roll-off frequency. The frequency response of the filter arrangement was determined by measuring the pressure inside the chamber while a known pressure pulse was applied to the chamber inlet. The pressures inside and outside of the filter were measured using commercial pressure transducers. The actual data shown on the right of Fig. 3 indicates that the frequency response of the fluidic filter follows the form of a one-pole electrical low-pass filter, as predicted.

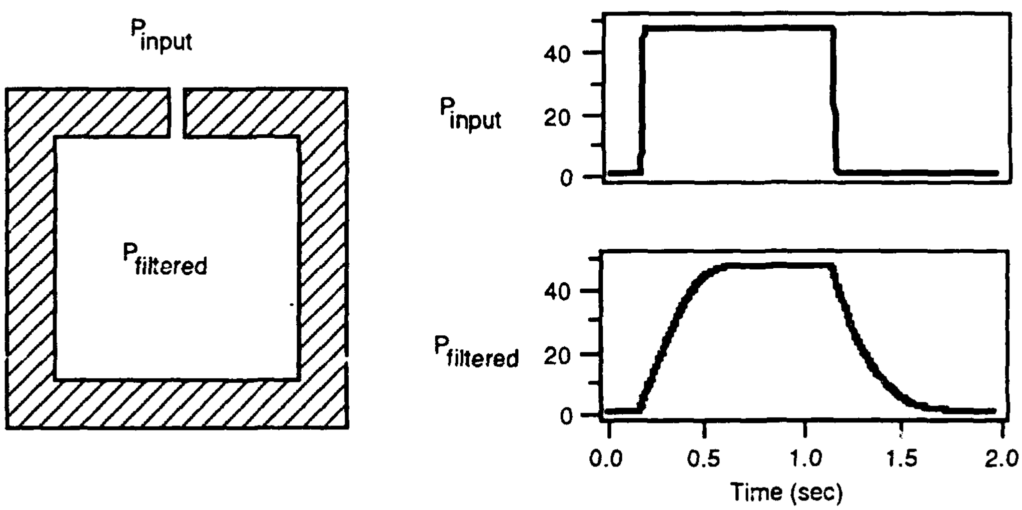

Figure 3. The fluidic filter simply consists of a restricted inlet connected to a volume. On the right, the actual data shows that the high frequency components have been filtered out of the sharp input pressure pulse.

The roll-off for such a filter is 20 dB per decade above the cut-off frequency. The cut-off frequency of the filter was adjusted to approximately 1 Hz.

The filter's measured frequency response is shown in Fig. 4. The MTM inside this filter is therefore effectively shielded from any high frequency pressure variations.

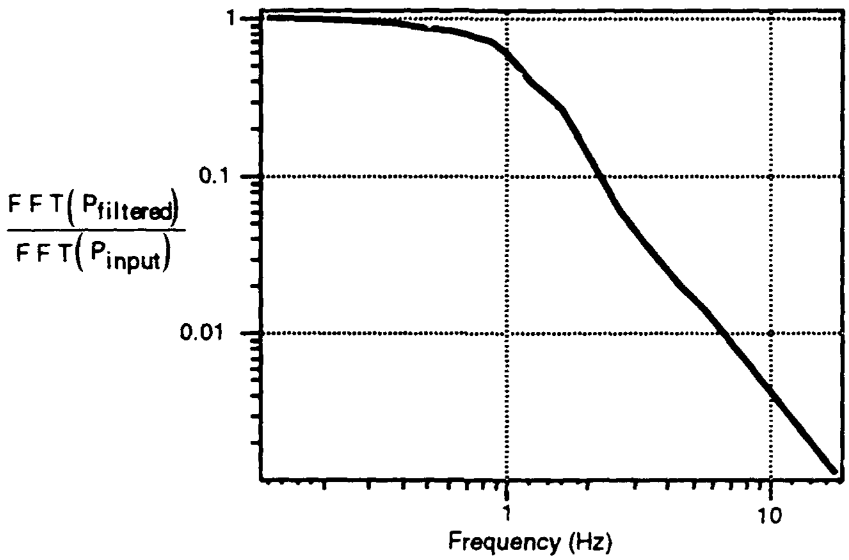

Figure 4. The pressure pulses, such as shown in Fig. 3, were used to determine the filter's frequency response. The filtered pressure and the input pressure pulses were fast-Fourier transformed. The frequency response is the ratio of transforms.

SENSOR ASSEMBLY AND INSTALLATION

Several factors were considered in determining the installed configuration of the sensors. First, the sensors were expected to experience several seconds of supersonic hot gas flow during the launch. Second, the sensors were to be surface mounted so as to require no permanent pad facility modification. Third, sensors were not to inhibit or be sensitive to the large amount of personnel traffic on the pad prior to launch. These factors dictated robust thermal and mechanical shielding for the filter containing the MTM.

The sensor subassembly and the encapsulated subassembly are shown in Fig. 5. The subassembly has an entry port connected to two separate chambers containing MTM. The smaller chamber had no restriction in its inlet, i.e., no filtering. The larger (~17 cm^3) chamber's inlet was restricted to three 0.52-mm-diameter holes in a 2.2-mm-thick copper disk. The MTM was encapsulated in latex sacks (toy balloons) and placed in both chambers. The latex sack provided accurate transmission of pressure to the tagged material, while easing recovery and preventing inadvertent clogging of the filter's holes. The subassembly was strapped to a base cast out of Martyte, a low-thermal-conductivity, high-strength, mineral-filled epoxy. To shield the chambers from temperature extremes during launch, Flamemaster Dynatherm product E300F, a thermal insulating material, was applied, leaving only the entry port opening uncovered. The photograph in Fig. 5 shows the sensor assembly at this stage, just before mounting on the pad.

The sensor assemblies were well bonded to the pad. The pad concrete was prepared with Dow Corning 1200 primer. A layer of GE RTV 11 was then applied to the primed concrete as a secondary primer/tie coat, and partially cured. RTV 162 was then applied to bond to the sensor assembly to the prepared area. The RTV 11 and RTV 162 were then cured together. This

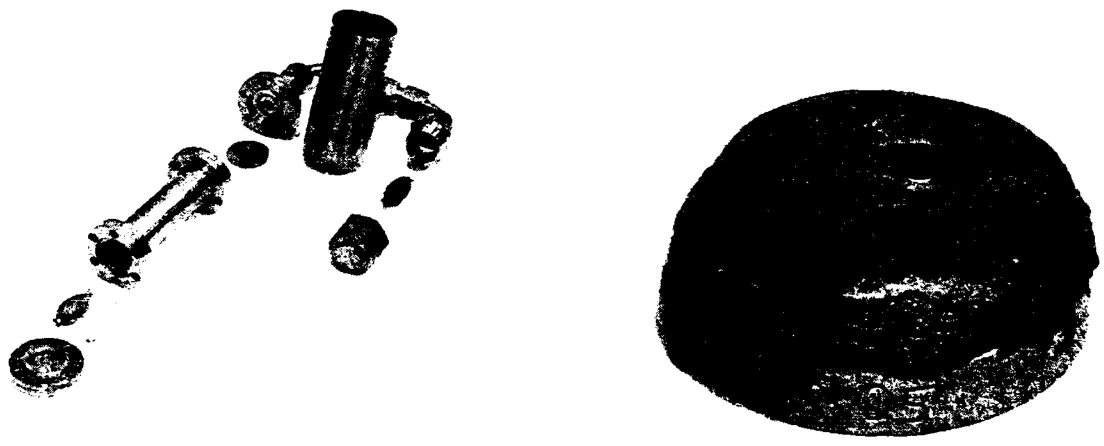

Figure 5. The subassembly parts are shown on the left, and the encapsulated sensor subassembly ready for pad mounting is shown on the right.

layered approach provided such a good mechanical bond that post-launch removal was strenuous. The sensor's aerodynamic profile was smoothed after mounting using additional Dynatherm material. Prior to launch, an aluminum foil disk was glued over the entry port to prevent any overspray from a launch water deluge system from entering. Tests showed the aluminum foil cover ruptured at ~5 psi, well below the MTM's sensitivity limit.

Twenty-nine sensor assemblies were mounted on the launch pad surrounding the Titan vehicle, as indicated in Fig. 6. This included positions of structural concern, where an active sensor system was also located. The closest sensors were within 15 feet of the centerline of one of the solid-fuel rocket motors. One of the sensors was placed on top of the launch tower to measure the peak pressure as the vehicle passed.

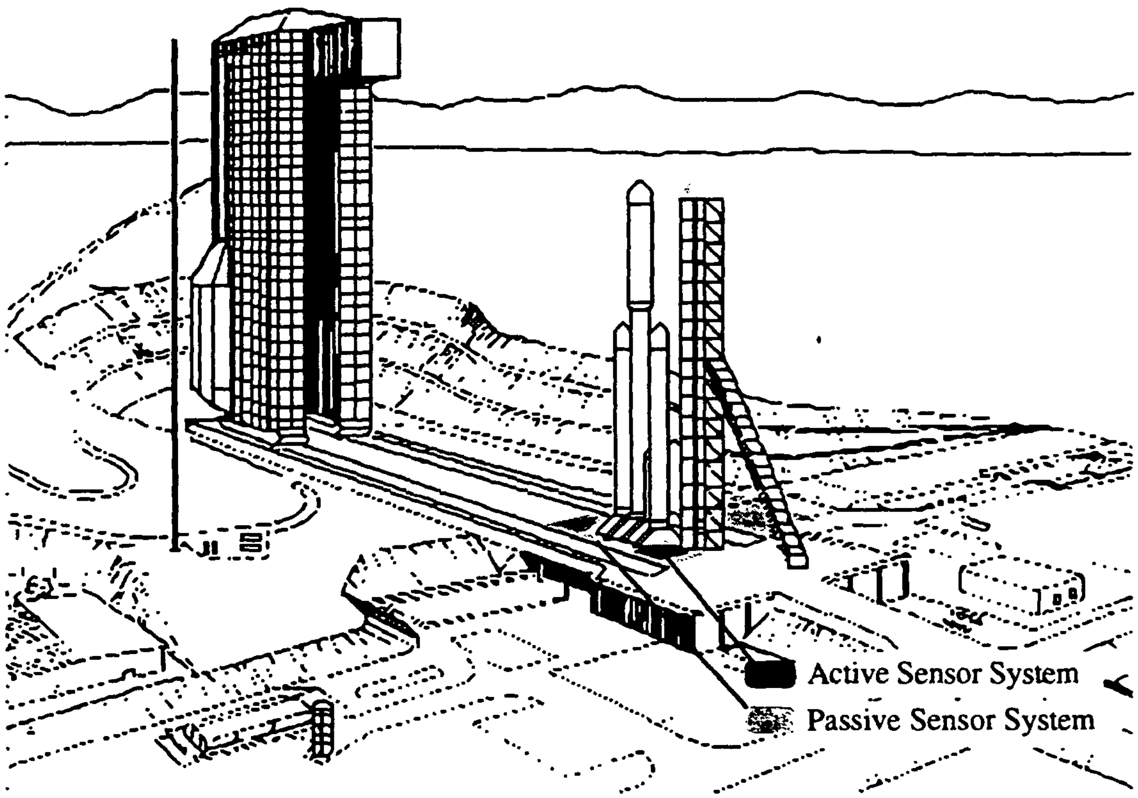

Figure 6. Twenty-nine microballoon sensor assemblies were mounted all around the pad, including on top of the launch tower. The active sensor system was limited to the immediate area of concern over the breezeway.

RESULTS AND CONCLUSIONS

Although the pressures accompanying the launch in the regions immediately adjacent to the flame bucket were initially expected to be quite high, the actual pressures experienced were relatively low. The active sensor system showed peak pressures of only 10 to 12 psig and average low-frequency pressures of 1 to 4 psig. The MTM/filter system appeared to perform flawlessly. Although the actual pressures were too low for the MTM/filter system to measure, the portability and robustness of the system had been demonstrated. Because of the portability of the system, we were able to install several sensors within a few feet of the lip of the flame bucket, immediately before the launch, without impacting the launch schedule. These sensors saw several seconds of direct plume impingement and recorded very high transient pressures. The recorded pressures were 120 psig and 45 psig at two different sites. It should be emphasized that these were transient pressures since they were only recorded by the non-filtered MTM. There was also evidence that hot exhaust gases entered the filter chamber of three of the sensors because the MTM sack was surface-charred in the exact pattern of the three entry port holes. The char did not extend into the grease, however, so the data were unaffected.

It is concluded that a combination of MTM and filter technology can be used to passively record peak pressures in hostile environments. It is envisaged that several filters tuned to various cut-off frequencies can be used to record peak pressures below these frequencies to obtain an approximation to the spectrum of the peak pressure.

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