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Development of FEM Model to Simulate Radiosonde Collisions

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Abstract. This paper deals with safety requirements for radiosondes and their possible finite element method (FEM) simulations. This article proposes a soft outer layer, which exhibits the use of a Polyurethane foam (PUR foam) layer on radiosondes. Analysis and tests of normal and PUR foam layer coated radiosonde's collisions with test targets were done. FEM models were created to model the collisions of radiosondes with virtual targets at drop tests in different scenarios. To compare and verify the virtual results, specified real-life drop test measurements were carried out. The measured data was analyzed and showed an average accuracy of 8% in force measurements, and 2.22% accuracy in duration of the tests. Based on these virtual and real-life tests it was demonstrated, that an FEM model can simulate the end result of using PUR foam layers on radiosondes. It also demonstrated that the applicable PUR foam layer increases a safer collision also increasing the chance of maintaining functionality of the radiosondes.

Keywords. Radiosonde, novel outer material, finite element method, PUR foam, drop test

1. Introduction

Light unmanned free balloons are regulated by Commission Implementing Regulation (EU) No. 923/2012 in the European Union and also categorized into light, medium, and heavy based on their payload mass and other properties. They are non-power-driven, lighter-than-air aircraft in free flight, often carrying payloads like radiosondes or individually made probes [1].

Typically, they are composed of a balloon, a parachute (except in some special designs), and a payload. These balloons are primarily used for meteorological data collection through compact instruments in radiosondes or for unique purposes through special designed payload packages [2].

This paper examines the current design of the modern era's radiosondes, which lack of soft outer layers and explores the potential solutions for enhancing safety through soft outer shells.

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It should be noted that the main body blocks of radiosondes are usually made from expanded polystyrene foam (EPS). Usually EPS is considered a soft material, but in this case it is tougher than polyurethane foam (PUR foam). The inner electronic parts are made partially of epoxy/glass fiber, polypropylene, a battery pack, etc. are placed in a self-stiffening way. This structure was analyzed in a previous work [3]. The usability of PUR foam for special designed balloon payloads was explored and proven in a previous paper, so this paper is connected to that research [4].

Mechanical properties of PUR foams can be used to get soft foam packaging for leading collision energy away [5-6].Volume distribution of foam cells within open cell foam structures is influenced by the log-normal distribution of sphere volumes. Foam models can be statistical analyzed of the encompassing cell volume distribution, the number of faces and edges, aligns closely with the properties of actual materials [7].

Finite element method (FEM) simulations were developed in previous researches to get a more accurate analysis of damaging processes [8]. FEM simulations were utilized in studies to analyze the performance of multilayer composite armors under the impact of high-velocity projectiles to further understand the damage and failure mechanisms within targets in addition. Gel-modified foam for shear stiffening against ballistic impacts were also modelled in FEM. These types of models consider various factors such as the angle of incidence, the shape, size, and frictional properties of the projectiles, as well as the thickness compaction from the production process [9-10]. The mechanical damages as bruises on fruits can be modelled in FEM which leads to considering a layered protective structure around of radiosondes [11]. The mechanical damage resistance of fruit transportation for safer food packaging was the topic in case of FEM simulations on the effect of expanded polyethylene (EPE) foam packing net [12]. However, this paper approaches issue with a PUR foam layer.

New methods for low velocity collision damage detection on composite materials and their structures were investigated. These methods can be used under 10 m/s impact speeds, the same values as in this study [13].

The characteristics of the primary colliding surface of the dropped body plays a significant role. A rigid surface would contribute to a higher peak force compared to a more deformable one. As current design lack's soft extra outer layers for force absorption during collisions, the potential for integrating such outer shells onto existing radiosondes or new payloads to enhance safety needs to be explored. A soft layered body might distribute the force over a larger area, as it increases the width of the body so the longer duration, potentially reducing localized stresses and thus the risk of damage, despite a possible higher peak force. Conversely, the "normal" body might exert a more concentrated force over a shorter duration, which could lead to more localized damage.

FEM simulations were employed to model the collisions of radiosondes with virtual targets in different scenarios. To compare and verify the virtual results specified real-life drop tests and measurements were done.

The purpose of this article is to implement an FEM model that can simulate drop tests of meteorological probes and can be verified with measurements. On the other hand, the further goal is to prove that PUR foam coating around the meteorological probe can significantly reduce the harmful effect of impact on the payload or an incidental human being.

2. Methods of drop tests with radiosondes

Virtual FEM drop tests were conducted with Ansys Workbench and also drop test in real-life to evaluate the simulations. Real-life drop tests were done at the Packaging Laboratory to measure the impact forces generated by two distinct payload configurations. The parameters of a normal Meteomodem trademark M10 radiosondes and an M10 radiosondes with a soft outer layer were modelled and tested. The goal was to verify that an extra layer of a soft material can absorb and redirect kinetic energy during an impact.

Each payload had an impact speed of 9.8m/s onto a C45 steel plate, measuring 800 mm × 520 mm × 20 mm (length × width × height). The dimensions of the M10 are 94 × 94 × 88 mm (length × width × height). It has a measured mass of 150g The soft shell was made from Smooth-On FlexFoam-iT! III PUR foam and was chosen in a previous paper [14]. The extra outer soft shell is 60mm in its height, and has a wall thickness of 14mm in all directions and has a mass of 21g. The 60mm height of the outer layer was chosen because at this size the M10's body can deform and there is still space that its pieces may even come apart. The downside was the indicated colliding surface.

Collision's different phases during an FEM or also real-life drop test do occur. These phases can be observed and described separately. Contact and first deformation of an outer layer. With a high deformable and energy-absorbing structure a gradual and relatively low increase in force can be seen. If the collision begins with a less elastic surface this dominant effecting phase would not occur. Transition to the less deformable parts happens after the deformable layers do lead more energy to them. Once the soft layer is significantly compressed, the force transmitted to the target plate begins to increase more sharply as the more rigid inner parts start to interact with the plate. After reaching the "theoretical maximum force" the parts are maximally compressed against the target plate. After this peak, the force could decrease as the energy from the impact dissipates and the materials begin to restore their original shapes. However, in complex systems force can increase by self-amplified movements after the bounce back. Damping occurs as the kinetic energy of the colliding object is converted into various forms of energy upon impact, and the system stabilizes.

2.1. Method of FEM drop test

An FEM drop test simulation has been run two version's three sub-versions (effectively 6 versions), with the previously mentioned main parameters. The FEM calculation was made with linear model. The meshing of the target plate and the soft outer shell had cubic forms, while all other parts had tetrahedral forms with optimized sizes. The normal radiosonde drop tests had 50935 elements and 14155 nods, while the soft layered had 59776 elements and 16364 nods. In the FEM model's system, the target plate was standing on three pressure cells as on which the plate would be placed in real-life. The generated forces of the system's collision are measured with them. In all, 6 versions of the collision were done. Firstly, 2 parallel face-to-face collisions with a normal and a soft shelled radiosonde. Secondly, 2-2 collisions were simulated with a normal and a soft shelled radiosonde tilted 2.5°and 5°. In these tilted versions a part of the edge got in first contact with the target.

The 3-3 version were done to get a broader spectrum on possible outcomes, as in real-life scenarios a perfectly parallel face-to-face impact is less possible, than with some angle which creates oblique force components. This means that the force of impact is not just perpendicular to the impacted surface, which leads to perpendicular and also to tangential components of force. The perpendicular components contribute to compression and potential deformation of the radiosonde, while the tangential component can introduce shearing forces and potentially cause the body to slide or skid after impact. Presumably a tilted body would lead to a lower peak force than in a parallel face-to-face version, and it would also have a longer impact duration. A side view of soft shelled face-to-face drop test simulation is shown on Figure 1.

(a) (b)

Figure 1. (a) soft shelled radiosonde before parallel face-to-face impact; (b) soft shelled radiosonde's maximal deformation during collision

2.2. Method of real-life drop test

In the real-life drop tests the whole process of collision was measured with pressure cells and also documented with high frame rate image recording. At these tests the impact forces were recorded five times for each design using pressure cells.

The Savitzky-Golay filtering technique, along with RStudio and the R programming language, were utilized for data analysis of the collisions [15].

Video documentation was captured on two-two occasions using an iX i-SPEED 3 high-speed camera, equipped with a Tamron AF 28-300mm f/3.5-6.3 XR Di LD Aspherical Macro lens. The footage was recorded at a frame rate of 2000 fps and a resolution of 1280×1024 pixels, allowing for detailed visual analysis of deformations in increments of 0.5 milliseconds.

It should be noted that minor discrepancies in the movement of the dropped bodies can be observed upon the impact on the frames, which were most probably caused by the gripper. It may not have released symmetrically on the handle of the radiosonde's cord, causing a slight rotation that exacerbated as the radiosondes fell. On the high frame rate images also impacts with approximately 5° tilted faces can be observed. In real-life impact at an angle creates oblique force components. This was the reason for doing 3-3 versions of FEM simulations and get a better on sight of possible outcomes.

3. Results of the drop tests

3.1. Analyzing the results of the FEM drop test

At a collision the duration and force need to be compared. The difference between normal and soft layer covered radiosondes can be clearly seen on Table 1. The FEM drop test was performed in 3-3 scenarios.

A soft layered radiosonde collides in average with 9.23% less force and 35.57% longer duration compared to the normal one's. In Table 1, the duration of collision, the maximal force, and the average forces were compared.

Table 1. FEM drop test measurements

Test	Maximal force (N)	Duration (ms)
Normal radiosonde	6450.47	2.95
Normal radiosonde 2.5° tilted	6382.9	2.98
Normal radiosonde 5° tilted	5220.5	3.0
Average	*6045.47*	*2.98*
SD	*1312.5*	*0.03*
Soft radiosonde	5758.1	3.7
Soft radiosonde 2.5° tilted	5178.0	4.2
Soft radiosonde 5° tilted	5526.3	4.22
Average	*5487.47*	*4.04*
SD	*231.8*	*0.29*

On Figure 2. the graphs of the simulated collisions are compared. The 1st graph is the average line of soft shelled radiosonde's drop test scenarios, the 2nd graph the average line of normal radiosonde's drop test scenarios. It can be clearly seen that radiosondes without a soft shell collide with higher force and shorter duration compared to the soft shelled ones.

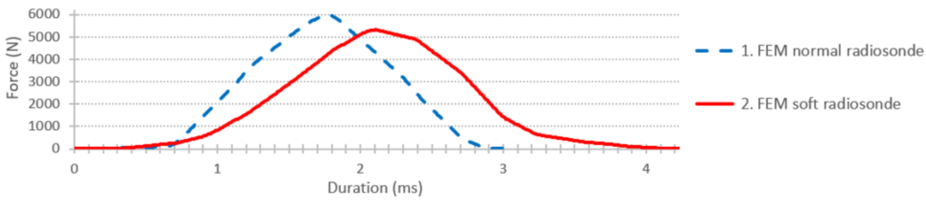

Figure 2. 1st graph is soft shelled radiosonde's FEM drop test average; 2nd graph is normal radiosonde's FEM drop test average.

3.2. Analyzing the results of the real-life drop test

Table 2 shows the processed data of the drop tests. By inspecting the average of the maximal forces it could be concluded that in average the soft shelled radiosonde caused 5.1% less force under a 26.88% longer collision time. This means that a 21g heavier extra shelled radiosonde would result with less damage compared to the more rigid normal radiosonde.

Table 2. Comparison between regular and soft layered drop test measurements

Test	Maximal force (N)	Duration (ms)
Radiosonde normal 1	5976.5	3.1
Radiosonde normal 2	6628.6	2.9
Radiosonde normal 3	6492.1	2.9
Radiosonde normal 4	6607.1	3.0
Radiosonde normal 5	5518.6	3.2
Average	*6244.58*	*3.02*
SD	*484.53*	*0.13*
Radiosonde soft 1	6390.5	3.7
Radiosonde soft 2	5981.4	4.2
Radiosonde soft 3	5685.5	4.4
Radiosonde soft 4	6047.2	4.2
Radiosonde soft 5	5536.4	4.2
Average	*5928.20*	*4.13*
SD	*332.84*	*0.26*

On Figure 3 two force-time graphs of the collisions can be seen. The 1st line is a normal M10 drop test, the 2nd line is the drop test of a soft PUR-foam layered radiosonde. By analyzing the difference between the normal and the soft layered radiosonde it can be seen, that the initial contact phase with PUR-foam layer is much softer. In case of a normal radiosonde's collision the graph of the force increases rapidly as there is no highly deformable material to translate and absorb energy at the collisions first phase.

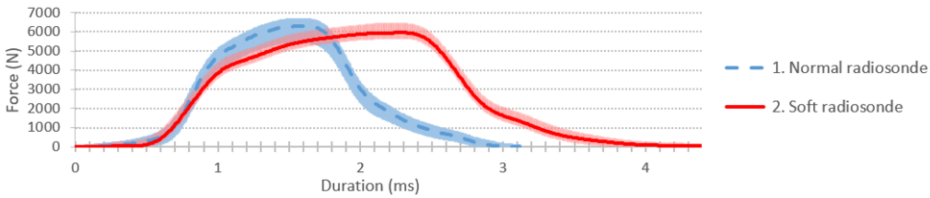

Figure 3. 1st graph drop test of normal radiosonde; 2nd graph drop test of soft shelled radiosonde

By analyzing the frames taken by high speed camera it can be stated that all phases of the collisions can be observed and categorized separately. Figure 4a shows a normal radiosonde's first contact with target plate. On Figure 4b the full contact and also maximal deformation of the radiosonde is shown. On Figure 4c the body left the target plate. On Figure 4d a soft PUR-foam layered radiosonde's first contact with target is shown. On Figure 4e the full contact with target surface is shown. On Figure 4f the body left the target plate.

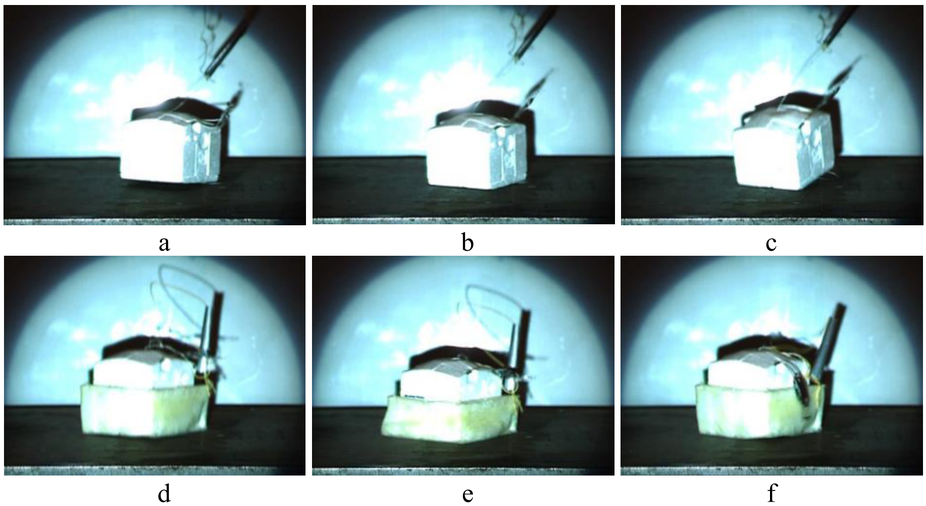

Figure 4. High-speed video frames at collision with two types of radiosondes: (a) normal radiosonde first contact with target; (b) a normal radiosonde's maximal contact and deformation; (c) a normal radiosonde's bounced back; (d) a soft shelled radiosonde's first contact with target; (e) a soft shelled radiosonde's full deformation; (f) the soft shelled radiosonde bounced back;

4. Conclusions

This development and testing have led to usable PUR foam layer structures on radiosondes. First, a special FEM model was developed, and implemented to simulate collisions with radiosondes in various drop test scenarios. A concept of using a soft outer layer, specifically a Polyurethane foam (PUR foam) layer, for radiosondes introduced. The study involved analyzing and testing the impact of both standard and PUR foam-layered radiosondes during collisions with test targets. In FEM the soft layer coated radiosondes cause in average 9.23% less force and have 35.57% longer duration at impact.

Second step was to validate the virtual results, so actual drop tests were conducted, and the data obtained was assessed. In real-life laboratory tests the soft shelled radiosondes caused in average 5.1% less force under a 26.88% longer collision time. The analysis revealed that the virtual tests with soft radiosondes and the real world tests had in average -8% error in force and -2.22% of collision duration, while in the case of normal radiosondes -3.3% error in force and -1.34% error of durations.

The study confirms that FEM models can effectively replicate the outcomes of using PUR foam layers on radiosondes, enhancing safety and increasing the likelihood of maintaining their functionality post-collision.

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