Why and How to Construct a Device for Hail Simulation

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***Abstract*—Hail characterization is necessary for generating models to protect people and their goods. Designing an electronic characterization system requires reproducing hail events. The objective of this article is to present a design proposal of a device for hail simulation based on the theory of energy matching. The simulator uses steel balls in place of hailstones. It can be loaded with up to 14 balls of sizes between 0.5 cm to 3.0 cm, which can be either dropped one by one or in pairs. If dropped in pairs, the distance between them can be regulated, as well as the delay. In this paper, the importance of having such a device is explained and several experiments to be conducted by using it in order to design a hail sensor are described.**

***Index Terms*—hail simulator, energy matching, calibration, sensor, design**

I. Introduction

Hail is a destructive climate phenomenon due to the massive short-time-span kinetic-energy discharge. In the Uruguayan agricultural sector, it causes significant economic loss [1] [2] since crops and greenhouse infrastructure are often damaged. So, why would anyone want to reproduce hail events?

A group of the Fluid Mechanical and Environmental Engineering Institute (IMFIA[1]), School of Engineering, University of the Republic (FIng, UdelaR) is looking forward to designing an early-detection system for hail. IMFIA has developed an equivalent system for floods [3], but models need feedback from the reality, then it is necessary to collect enough reliable information on regional hailstorms. Doing so requires several hail sensors deployed as a network in the region of interest.

Networks traditionally deployed to analyze hail event characteristics have several tens of non-electronic single-use nodes [4] [5]. After a hailstorm, each sensor must be collected, manually analyzed and replaced. They don't collect temporal data, therefore information is overlapped if exposition to several hailstorms occurs. This work is manpower demanding: an electronic automatic hail-sensor network will let climate researchers focus on the data processing instead of its acquisition, bringing them closer to hail forecasting. Existing automatic sensors are not affordable or non-commercial. Therefore, we are developing a trustworthy cost-effective hail sensor, customized to IMFIA's group needs.

For a general overview, the sensor we are designing works as follows (fig. 1). There is a plate (a) to be struck by hailstones (b). Each impact provokes an acoustic wave (c) that propagates within the plate, generating instantaneous micro-strains on the surface. A piezoelectric diaphragm (d) fixed on the surface of the plate converts the strains to a voltage signal, which is acquired by means of an acquisition board (e).

The acquired electrical signals must be related to the physical phenomenon of the hailstone hitting the sensor. Each signal is the convolution of the impulse the projectile applies, the propagation within the plate and the transducer's response. Knowing the latter ones, signal-processing techniques such as envelopment detection by means of Hilbert's transform and impact-signal isolation by means of Hanning window can be applied to obtain information on the characteristics of the projectile. Calibration [6] for relating the energy of the acquired signals to the mechanical

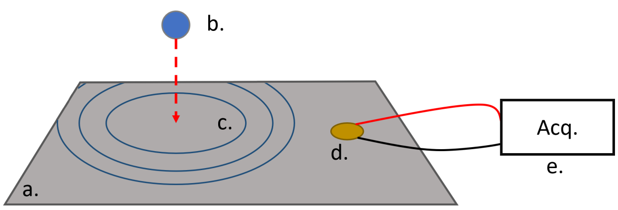

Fig. 1: Sensor overview.

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[1]Every Uruguayan institution's acronym is given for it's name in spanish.

energy of the striking projectiles, is crucial. Several specific situations of interest, regarding impact energy, point of incidence and simultaneous strikes must be considered within calibration. Repetitiveness of the measurements must also be proved. It is impossible to perform such an activity by using real hail: a device that reproduces hail impacts is required to calibrate the sensors. This paper presents the design of a hail simulator implemented at FIng, UdelaR. It is mainly approached from the user point of view, explaining experiments that must be achieved.

Having a machine that simulates hail impact will let us perform experiments several times in a repetitive manner in controlled laboratory conditions and without the need of neither natural hail, which is extremely difficult to get or synthetic hail, which is also hard to prepare and handle. Moreover, the method we chose for simulation doesn't require any consumable goods, the projectiles can be reused as many times as necessary since they are not damaged upon experiment execution.

The second section of this paper presents two options for achieving hail simulation and explains our choice. In the third section, the energy matching theory is explained. The fourth section presents the requisites on hail characterization and on the hail simulator. The fifth section explains driven preliminary tests. Section six presents results regarding the experiments of section five, concluding that for designing a hail sensor, a hail simulation device is absolutely necessary. In the seventh section, a general idea on the simulation device is given. Finally section eight explains the immediate-future work.

II. Chosen simulation strategy

The main problem with hailstorms is their elevated destructive power. Therefore, the quantity of interest for the sensors is the diameter of each impacting hailstone. This is related to the kinetic energy at the time of impact, which is typically used for characterization [7]–[9].

One way of simulating hail impact is using a compressed-air gun. This is a good choice for testing solar-panel [10] or crop damage [11], as well as hail-protection systems [12] and jet-engine air-inlet resistance to hail [13]. This test can take place in a regular-sized room, but its accuracy regarding the impact energy and the precision on the impact point is poor for our intentions.

We chose to use a technique called Energy Matching [14], that will be explained in the next section. Therefore, we must drop balls, for which we chose steel as a material, from a height that depends on the diameter of the hailstone we want to simulate. We designed a machine for doing so, which is currently on construction. This kind of device was roughly described in [14] and [15]. The referenced devices had few requirements on impact point repetitiveness, since they needed to hit the sensor at any point. The former of them, describes a guided fall, in which friction seems not to be considered.

Since the point of impact is crucial for tests and calibration, precision must let us get most of the impact within a 0.5 cm-diameter circle around a center which should be accurately closer than 0.5 cm to the aimed point. The drop-height control must be automated and as accurate as 5 cm. Once positioned in height, it should be possible to unload the full loader without a vertical displacement. An electromagnet will let us achieve zero initial velocity. There must be possible to drop two equal balls with a controlled or null delay, in order to test the response of prototype sensors to simultaneous strikes.

III. Energy Matching

According to this technique, steel balls can be dropped from a height (h_{drop}), so that their kinetic energy at the time of impact against the sensor ($E_{ball}^{@impact}$) equals the terminal energy of a natural hailstone of known characteristics falling from formation point. Matching also the hailstone and ball diameter d reduces the amount of changed variables which could affect the propagated waves. Here is considered that the distance traveled by the hailstone is so large, that it reaches terminal velocity, whereas the distance traveled by the ball is short enough as to say that energy is conserved. Due to the energy conservation of the ball, we can use the potential energy of the ball at the drop instant, which is in explicit relation to h_{drop}, instead of $E_{ball}^{@impact}$. Calculating the terminal velocity, of the hailstone and its energy as in [4] [14], we get (1), where ρ_h, ρ_s and ρ_a are the mass densities of hail, steel and air and c_D is the drag coefficient of the atmosphere.

$$h_{drop} = \frac{2}{3}\frac{\rho_h^2}{\rho_s \rho_a c_D} d \quad (1)$$

The main advantage of this technique is that impacts can be better controlled than with the air gun in terms of precision and accuracy. Nevertheless, though drop height is extremely reduced when using a high-density material, heights needed for matching energies are still large and performing the technique adequately requires a device such as the one described in this paper. Aiming with this device from the required heights is much more feasible than aiming at the restrained surface of the sensor from the much longer distances artificial ice spheres, which are difficult to prepare and handle, would require.

Several hypothesis regarding the hailstones are made to generate models we can work with, as in [16]: hailstones are homogeneous ice spheres, reach terminal velocity, are hard and don't disintegrate upon impact. Atmospheric parameters are constant.

IV. Requisites

The device is constructed to simulate hailstones in a range of diameters of $[5 - 30]$ mm. Using steel balls for energy matching, the kinetic energy will be up to 3.5 J by dropping the projectiles from the height range of $h_{drop} = [0.5 - 4]$ m. It must be possible to simulate the occurrence of two hailstones impacting the sensor within an interval of $\Delta t = 10$ ms. Experiment repetitiveness is crucial. The ball drop must be triggered with an order of the user.

The electrical energy of the signals acquired with the piezoelectric diaphragms can be related to the mechanical energy that the stone transfers to the plate. The transferred mechanical energy is a part of the kinetic energy of the falling hailstone at the time of impact. Observing energies is the main approach, but other aspects must also be considered, for instance the frequency spectrum response of the piezoelectric transducers and the impulse response of the sensor's plate.

The shape and material of the plate are crucial for the behavior of the acoustic waves, since some allow a richer frequency spectrum than others, thus determining the quality of the obtained electrical signal. The way the plate is fixed to the ground does also affect wave propagation. Therefore, the following experiments will be sequentially performed to chose the plate's material among a selection of reasonably weather and impact resistant ones (stainless steel, aluminum, acrylic and tempered glass).

1) Acquire signals regarding impact of projectiles with different kinetic energies, hitting at the same point of the plate, one by one.
2) Acquire signals regarding impact of projectiles with equal kinetic energies, hitting at different points of the plate, one by one.
3) Acquire signals regarding impact of two projectiles hitting on two points of the plate at nearly the same time, repeat changing the distance between impact points.

Once the material is chosen, the set of experiments will be repeated for choosing shape of the plate. The area of the plate must be big enough as to catch a significant amount of hailstones during the event, but small enough for the waves to interact with the borders, which is beneficial for acquiring informative signals.

The thickness of the plate depends mainly on the mechanical resistance of each material. Fixation method and position of the transducers will be determined afterwards. Wind conditions must also be simulated, therefore experiments where the impact is oblique to the plate will be performed. In the preliminary experiments, it has been observed that the plate must be fixed to a heavy base in order to avoid undesired movement after an impact.

Security precautions, such as an alarm and physical barriers must be implemented as a part of the simulation system.

V. Preliminary tests

We have driven several experiments on plates of the considered materials as a proof of concept. The reference shape for the plate is a square with an area of approximately $800\ cm^2$. Tests were performed by dropping steel balls of $d = \{10 : 5 : 25\}\ mm$ from $1\ m$ height, aiming to the plate center. The kinetic energy is thus in the range of $[40 - 600]\ mJ$. An electromagnet was used for performing the experiments in a repetitive way and for assuring null initial velocity. The aim point is only changed for tests regarding the impact position. One piezoelectric is fixed at $(\frac{1}{2}, \frac{1}{4})$ of the plate, in normalized coordinates. Tests have also been driven for observing whether two simultaneous impacts can be told apart. For this, we dropped two balls by using the same electromagnet. We used a system for laboratory experiments with a NI USB6210 acquisition board and a PC.

VI. Results on preliminary tests

We have observed that for a given plate and given conditions of the experiment, the acquired signals are highly repetitive. On the other hand, when changing the impact point the signals change significantly. This is because the wave propagation paths change completely. Also, a useful proportionality between acquired signal's energy and kinetic energy has been observed for most of the materials, which is shown in Table I.

It has been empirically observed that, when performing the experiments with acrylic, a greater percentage of the energy is transferred to the plate when the ball is small than when it is big, whereas this relation is inverted when the plates are metallic. This phenomenon regards the elastic properties of the materials.

In Fig. 2a, the signal when performing the explained experiment with 25-mm ball impacting a stainless-steel square plate at the center is shown. The frequency spectrum of the signal is shown in Fig. 2b. It can be observed that the signal has a duration of some milliseconds. Some microseconds after the impact, the signal reaches its maximum, having a steep decay afterwards. The decay decelerates, having in consequence a long signal. It seems possible to work only with the beginning of the signal, having thus shorter dead time. Regarding the spectrum, the signals were sampled at $80\ kHz$, therefore the maximum frequency that could be represented is $40\ kHz$. We confirmed that the sampling frequency is adequate, since all of the signals have a shorter bandwidth than $10\ kHz$.

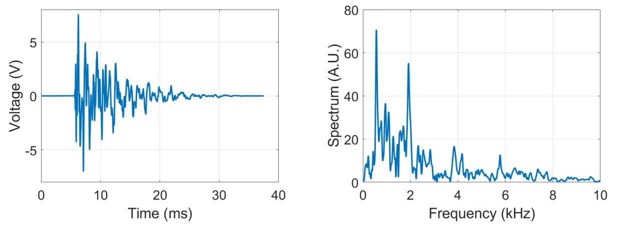
VII. Simulation device

The device we are building is divided in three main parts: launcher-loader (Fig. 3a), rotation platform (Fig. 3b) and elevator (Fig. 3c). In the launcher-loader, the loader holds balls and drops them one by one to the launcher, which holds a single ball until ordered to drop it. The elevator controls the drop height. The rotatory platform holds the sensor.

The loader works by the same principle as the cylinder of a revolver, having eight partitions, seven of them will be loaded and one must remain empty. The floor has a hole of the size of the partitions and turns around one place every

TABLE I: Energy comparison

	Energy in % of that of the biggest ball.				
	Kinetic	Electric using different materials as a plate			
d (mm)	at impact	Glass	Steel	Aluminum	Acrylic
25	100	100	100	100	100
20	51	79	77	118	41
15	22	57	60	103	21
10	6	24	31	67	10



(a) Time signal (b) Frequency Spectrum

Fig. 2: Signal obtained in the experiment with the steel plate and the ball of $d = 25\ mm$, along with its frequency spectrum.

time a ball will be dropped to the launcher. The loader and the launcher are connected in a manner that softly guides the ball, not shown in the figure.

The launcher is a hollow cube without the top face. A side face was replaced by a mobile door, which is moved by a stepper motor through a crank-connecting rod system. A relay-controlled electromagnet is inside the door, to move the ball to the drop position and hold it until the order to drop is received. Afterwards, the door returns to the original position.

In the launcher-loader arrange of Fig. 3a, the loader is fixed meanwhile the launcher can be manually set into different positions by means of a dented ruler. Two such launcher-loader devices side by side in the elevator will let us perform the experiments of quasi-simultaneous impacts.

The elevator consists of a $0.6\,m \times 0.4\,m \times 1.5\,m$ aluminum structure with a stepper motor. The launcher-loader devices are hosted in two roller guides that serve as track for the $1\,m$-vertical movement the motor must exert over them. The movement will be aided by a pulley system. This structure will be placed attached to a wall.

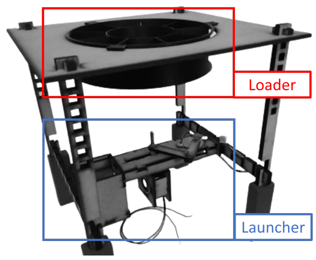
The rotatory platform is the base for the sensor on the ground and permits to manually change the zenith angle of the sensor in order to simulate the effect of wind in the hailstones. The angles of interest are discrete, $0° : 5° : 45°$.

VIII. Conclusions and Future Work

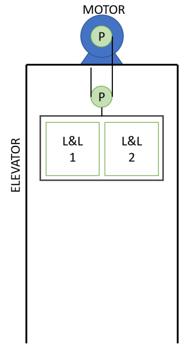
An automatic hail simulation device, based on the theory of energy matching was designed. This machine will let us calibrate hail sensors.

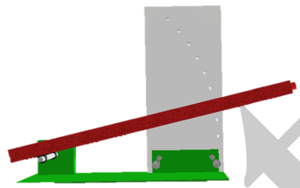
The preliminary tests show the dependence between the energy of the signal and the energy of the balls in a small range. It has been observed that some materials have better performance than others. In the conditions of the experiment, tempered glass, acrylic and stainless steel have excellent performance, whereas there is no relation between energies for signals acquired with aluminum. We suppose that a reason for this is that in aluminum small balls transfer more energy to the plate, whereas the big ones preserve more energy, therefore bounce higher.

The need to construct a machine with high precision and accuracy for impacts was noticed and therefore we developed the device presented in this work. It will let us

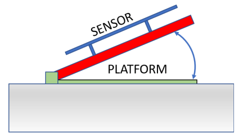


(a) Launcher and loader





(b) Rotatory platform



(c) Simulation system

Fig. 3: Main mechanical parts of simulation device.

calibrate the energies and perform several tasks in order to have detailed information on the behavior of different plates when receiving well known impacts.

In the immediate future, the hail simulation device will be finished and the posed experiments will be repeated using the device.

Firstly, every constructive detail regarding the plate will be decided. Orderly, we will: choose a material for the plate, decide the shape of the plate, find the best way of fixing the plate, decide the position of the piezoelectric diaphragms on the plate and choose the best model of those transducers for this application. Secondly, we will thoroughly study the outcome of the plate, particularly the energy of the acquired electrical signals, regarding certain inputs of interest: relation between energy of measurements and kinetic energy at the time of impact, dependence of energy of measurements with the impact point, and dependency of energy of measurements with the angle of incidence. Correction algorithms must be proposed for the dependencies in order to have a useful system.

Other experiments of interest can be performed with this device, for instance dropping balls of different size in order to match their energy and check whether the size of the ball effectively changes the acquired signals.

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