Implementation and Evaluation of a Hail-Impact Simulation Device

Implementación y Evaluación de un Dispositivo de Simulación de Impactos de Granizo

Implementação e Avaliação de um Dispositivo de Simulação de Impacto de Granizo

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Summary. - Hailstorms are hazardous for people and goods. Automatically collecting information on hailstorms will help climate researchers analyze them and generate models for forecasting. Reproducing hail impacts is a requisite for designing and calibrating an electronic hail sensor. In this article, the design of a device for hail-impact simulation is presented. This device is based on the theory of Energy Matching, which explains how steel balls can be used instead of hailstones in order to have equivalent impact energies. The posed device, which can perform up to fourteen impacts between loading instances, either by dropping balls one by one or in pairs, was constructed. The size of the balls can be between 0.5 cm and 3.0 cm. In this paper, which is an extension of the work originally presented at the URUCON2021 conference, the importance of having such a hail-impact simulation device is explained. The main contribution of this extended work is the presentation of an experiment performed as an application of the constructed device. This experiment has the objective of verifying the aiming repetitiveness, while also verifying the linear relation between impact and electric signal energies.

Keywords: Hail-Impact Simulator; Energy Matching; Calibration; Sensor; Design.

Resumen. - *Las tormentas de granizo son peligrosas para las personas y sus bienes. Automatizar la obtención de información sobre tormentas de granizo permitirá a los investigadores del clima a enfocarse en analizar los datos y generar modelos de pronóstico. Reproducir los impactos es un requisito para diseñar y calibrar un sensor electrónico de granizo. Presentamos el diseño de un*

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dispositivo para simular impactos de granizo basado en la teoría de emparejamiento de energías, que explica cómo se pueden utilizar bolas de acero y obtener impactos equivalentes en energía a los de piedras de granizo conocidas. Contruimos el dispositivo propuesto, que puede soltar bolas de entre 0.5 cm y 3.0 cm. En este artículo, que es una extensión del trabajo presentado originalmente en la conferencia URUCON2021, se explica la importancia de tener un dispositivo de simulación de granizo de estas características. La principal contribución de este trabajo extendido es la presentación de un experimento que se realizó como aplicación del dispositivo construido. El experimento tiene los objetivos de verificar la repetitividad de la puntería y verificar la existencia de una relación lineal entre la energía cinética del impacto y la energía eléctrica de las señales adquiridas.

Palabras clave: *Simulador de Impactos de Granizo; Emparejamiento de Energías; Calibración; Sensor; Diseño.*

***Resumo**. - Chuvas de granizo são perigosas para as pessoas e suas propriedades. Automatizar a coleta de informações sobre granizo permitirá que os pesquisadores do clima se concentrem na análise dos dados e na geração de modelos de previsão. Reproduzir os impactos é um requisito para projetar e calibrar um sensor eletrônico de granizo. Apresentamos o projeto de um dispositivo para simular impactos de granizo com base na teoria do emparelhamento de energia, que explica como bolas de aço podem ser usadas e obter impactos equivalentes em energia aos de granizos conhecidos. Construímos o dispositivo proposto, que pode lançar bolas entre 0,5 cm e 3,0 cm. Neste artigo, que é uma extensão do trabalho originalmente apresentado na conferência URUCON2021, é explicada a importância de se ter um dispositivo de simulação de granizo com essas características. A principal contribuição deste trabalho estendido é a apresentação de um experimento que foi realizado como aplicação do dispositivo construído. O experimento tem como objetivos verificar a repetibilidade da mira e verificar a existência de uma relação linear entre a energia cinética do impacto e a energia elétrica dos sinais adquiridos.*

Palavras-chave: *Simulador de Impacto de Granizo; Casamento de Energias; Calibração; Sensor; Projeto.*

1. Introduction. - This paper is an extension of the work originally presented at the URUCON2021 conference (1). It presents the design of a hail-impact simulator implemented at FIng, UdelaR. The device, named SGran, is mainly approached from the user's point of view, suggesting experiments for which it will be useful. The main contribution of this extended paper regarding the former one is the addition of the description and results of an experiment driven with SGran. This experiment is realized in order to verify the feasibility of identifying the energy that a ball transfers to a plate from the signal acquired with piezoelectric transducers.
Hail has been studied for decades in several countries where it occurs, such as the USA (2), China (3), Japan (4), Germany (5), Italy (6), Spain (7) and Uruguay (8). In this article, the need to reproduce hail events is explained, the main ideas of how to construct a device for doing so are given and the results of an experiment are shared.
Hail events are highly destructive. The mean duration of hailstreaks is in the order of 10 minutes (9)(10). During this time, hazardous amounts of kinetic energy are discharged. In the agricultural sector, it causes significant economic loss due to crop and greenhouse damage. In Uruguay, hail damage to assets is a great risk to agricultural investments (11)(12)(13).
Vehicles are other usually damaged goods, as shown in Fig. I. Hail forecast is of extreme importance for vehicle owners to shelter them. Having the hail-impact quantification in an area would help insurance companies to have reasonable policies regarding hail damage (14).

Figure I. - Hail damage on vehicles (15)

Solar panels are structures that can receive a direct impact from hail. Even though they must comply with international regulations for commercialization, hail characteristics differ significantly across the world. It would be therefore more efficient for every regulator to know the specific characteristics of hail in their area, for having specific regulations.
A Uruguayan research group focused on fluid mechanics and the environment is looking forward to designing an early-detection system for hail (Fluid Mechanical and Environmental Engineering Institute - IMFIA). IMFIA researchers have developed an equivalent system for floods that helped prevent them in a region of the Uruguayan territory that had several related incidents (16)(17). Elaborating such a system requires modeling reality: achieving an accurate model needs input information and feedback. It is therefore necessary to collect enough reliable information on regional hailstorms.
Networks traditionally deployed to analyze hail-event characteristics were formed by several tens of single-use nodes (18)(19). The main device for collecting hail-impact information is the hailpad: a foam sheet with an aluminum covering, where each impacting hailstone leaves a dent on the surface. If the pads were exposed to several hailstorms, there is no time-dependent data information. So, each unit has to be replaced between hailstorms. Therefore, hailpads are disposable. The analysis on these devices is observational, demanding qualified observers for interpreting the information. An electronic automatic hail sensor with characteristics to be placed in a network would expand climate researchers' possibilities, who would focus on high-level data processing instead of its acquisition. This would bring people a better understanding of hailstorms,

enhance the nowcasting of their information and bring climate researchers closer to accurate hail forecasting.

Existing automatic sensors are not affordable or non-commercial (20) (21). Therefore, our motivation is the development of a hail sensor that is cost-effective and trustworthy to be used by environment researchers. The final product must be deployable in a network in the region of their interest. The proposed sensor is based on recording acoustic waves using piezoelectric transducers. Therefore, a big load of the development effort is being put on selecting a structure and transducer disposition that permits the acquisition of a signal rich in impact information, for extracting useful characteristics.

Here is a brief description of how the sensor we are designing works (Fig. II). The body of the sensor has a plate that is exposed to hailstone impacts (a). During a storm, a hailstone strikes the plate (b). An acoustic wave origins at the impact point and propagates within the plate, generating instantaneous micro-strains on the surface; boundary conditions cause reflections that add to the direct wave (c). A transducer consisting of a piezoelectric diaphragm, which is fixed on the lower surface of the plate, converts the strains to a voltage signal (d). The electric signal is acquired by means of an acquisition board (e).

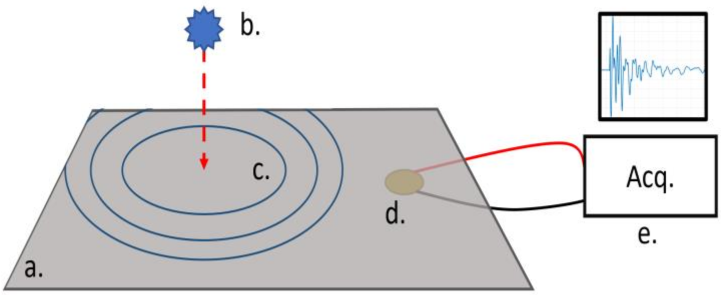


Figure II. - Sensor overview.

Each acquired signal corresponds to the sampling of the resulting electrical signal generated by the piezoelectric transducer when the physical phenomenon of a hailstone hitting the plate occurs. The resulting electrical signal, v(t), is a time function composed of the convolution of three time functions, as in Eq. (1).

$$v(t) = f_1(t) * f_2(t) * f_3(t) \tag{1}$$

- $f_1(t)$: the impulse applied by the projectile.
- $f_2(t)$: the propagation within the plate.
- $f_3(t)$: the response of the transducer.

Having enough previous information on $f_2(t)$ and $f_3(t)$, signal-processing techniques can be applied to obtain information on the characteristics of the projectile. Such techniques involve maximum detection, time-windowing, filtering, computing frequency spectrum, and quantifying energy within an appropriate band.

Calibration projectiles (22) for relating the energy of the acquired signals to the mechanical energy of the striking stones, are crucial. This does only make sense if the energy computed from the electrical signal has univocal dependence on the energy of the impact, which will be further analyzed in this work. There are several variables that affect the result, such as the point of incidence, the point of reception (where the transducer is located), and the material and shape of the plate. It is also interesting to know how the sensor would manage simultaneous strikes. For calibration procedures, the repetitiveness of the measurements is a requisite. Therefore, it is impossible to perform such an activity by using real hail: a device that reproduces hail impacts is required.

Having a machine that simulates hail impact lets us perform repetitive experiments using controlled laboratory conditions. This device saves us, until an advanced stage of the hail-sensor project, the need for synthetic hail, which is difficult to prepare and handle. Simulating hail impacts with this device doesn't require any consumable goods: the projectiles can be reused as many times as necessary since they are not damaged upon experiment execution. All the tests needed to develop the hail sensor will be performed first with aid of the machine we present in this work. Artificial hail will be seldom necessary. Since obtaining natural hail is extremely unpredictable, it will be avoided until having an advanced prototype of the hail sensor.

This first section of the paper was an introduction to the hail problem and the utility of developing a hail-impact simulation machine. The second section presents the basis of hail-impact simulation, approaching different strategies, explaining the *Energy Matching* theory, and then detailing the requisites a hail-impact-simulation device should comply with in order to be useful for the techniques we are looking forward to performing. In the third section, the materials and methods are presented. Those are divided into a preliminary test, the design of the simulation device, which was named *SGran,* and an application of *SGran*. The fourth shows and analyses the results regarding the preliminary tests and the ones performed with the constructed device. Finally, in the fifth section, the conclusions and future work are presented.

2. Basis of Hail-Impact Simulation. –

2.1. Chosen strategy. - Hailstorms are very hazardous due to the elevated destructive power from the kinetic energy of the hailstones. Therefore, the quantity of major interest for the sensor is the kinetic energy at the time of impact, as considered in (23; 24; 20), which under some hypotheses is directly related to the diameter of the hailstone. Hypotheses are necessary to generate models we can work with; we use the following ones (25) (26): hailstones are homogeneous ice spheres, reach terminal velocity before the impact, are hard, and don't disintegrate upon impact. Atmospheric parameters are constant.

One way of simulating hail impact is using a compressed-air gun with spheres of ice as projectiles. This is a good choice for experiments with low impact-point-precision and impact-energy-accuracy requirements, such as testing hail-protection systems (27) or crop damage (3). This also works with medium precision and accuracy requirements, for instance testing solar panels (28), as well as jet engine air-inlet resistance to hail (29). An advantage of this impact simulation option is that it can take place in a regular-sized room.

We chose to perform experiments based on a theory known as Energy Matching (26), which will be explained in the next section. This theory justifies hail-impact calibration techniques that are performed by dropping balls of a higher density than the hail. We chose steel as a material since it has several advantages as being dense, magnetizable, robust, and solid bearing balls of several diameters are easy to find. We designed and constructed a machine for dropping the steel balls in compliance with all the requisites of the experiments to be carried out. Ideas for this device were roughly described in (26) and (30).

In our case, the point of impact is crucial for tests and calibration. For testing the response of prototype sensors to simultaneous or quasi-simultaneous strikes, it must be possible to drop two balls at the same time or with a programmed delay in the order of milliseconds. Therefore, a part of the mechanism must be duplicated.

2.2. Energy Matching. - According to the Energy Matching theory, solid balls of a material of higher density than hail can be dropped, so that their kinetic energy at the time of impact against the sensor, $E_{ball}^{@impact}$, equals the energy that would have a natural hailstone of known characteristics falling from formation point, $E_{hail}^{@impact}$. The Energy Matching theory is based on the hypothesis 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 to neglect the effect of friction against the air, thus considering the ball fall as energy conservative. Terminal velocity is the final speed that objects falling from large heights reach. It occurs when the force regarding friction with the surrounding air, which is speed dependent, equals the gravity force. In this analysis, the wind is disregarded.

The energy of the ball at the drop instant, $E_{ball}^{@drop}$, is in direct relation to the drop height, h_{drop}, as shown in Eq. (2). The impact energy of the hailstone can be calculated as in Eq. (3) (18; 26), where d is the diameter of the hailstone. After choosing the ball material, it exists only one combination (h_{drop}, d) of the ball that matches the energy and the diameter of the hailstone. This reduces the number of variables that could affect the acoustic response in the plate. Then, d and h_{drop} will be the only variables of the system, related as in Eq. (4), 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, considered a constant (26).

$$E_{ball}^{@drop} = mgh_{drop} \tag{2}$$

$$E_{hail}^{@impact} = \frac{\pi\rho_h^2 g}{9\rho_a c_D} d^4 \tag{3}$$

$$h_{drop} = \frac{2}{3}\frac{\rho_h^2}{\rho_s\rho_a c_D} d \tag{4}$$

The main advantage of this technique is that impacts can be better controlled than with the compressed air gun in terms of precision and accuracy: the *SGran* solves the problem of aiming accurately and hitting repetitively. Nevertheless, though drop height is extremely reduced when using steel due to its high density, the heights needed for matching some energies are still larger than those of a regular ceiling height.

2.3. Requisites on Impact-Simulation Device. - The device is constructed to simulate the impact of hailstones in a range of diameters of [5 - 30] mm. Given that the density of steel is $7850\,\frac{kg}{m^3}$, the kinetic energy will be up to 4.5 J by dropping the projectiles from the height range of h_{drop} = [0.5 - 4] m. When performing experiments of double impact, the delay between strikes must be in the range [0 - 10] ms. Experiment repetitiveness is crucial: accuracy on the aimed point must be 0.5 cm, as well as precision on the impact point for repetitions. The drop-height control must be automated, with a 2 cm accuracy. Once positioned at the desired height, it must be possible to command a sequence of ball drops, without a vertical displacement. It is crucial to achieving null initial velocity. The ball drop must be triggered with the 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. The main approach for measuring the impact energy is finding a direct relation between the impact energy and the energy of the signal. For calculating the energy of the signal, it is interesting to analyze its frequency spectrum, in order to choose an appropriate frequency band to work with, avoiding frequencies for which noise is predominant. The spectrum is strongly dependent on the frequency response of the piezoelectric transducers and the response of the sensor's plate when an impulse is applied at the impact point.

The behavior of the acoustic waves is strongly dependent on the material, shape, and dimensions of the plate. Some boundary conditions allow a richer frequency spectrum than others. The area of the plate must be big enough to catch a significant amount of hailstones during the event, but small enough for the waves to interact with the boundaries, which is beneficial for acquiring informative signals. A signal with a rich spectrum gives information of special interest for detecting the impact point. Knowing where the strike occurs may be interesting for correcting signal-energy differences when equal projectiles impact different zones of the sensor. How the plate is fixed to the ground also determines boundary conditions.

The designed device allows the use of the enumerated experimental conditions:

1. Projectiles with different kinetic energies, one at a time. Fixed impact point.
2. Projectiles with equal kinetic energies, one at a time. Variable impact point.
3. Two projectiles hitting simultaneously on different points of the plate. One of them hits at a fixed impact point. Repeat the experiment by changing the distance between both impact points.

Several characteristics of the plate will be selected as a result of this set of experiments, such as material, shape, fixation method, and position of the transducers. Preliminary experiments have shown that the plate must be fixed to a steady base for avoiding undesired movement after an impact. In real conditions, it would be fixed to the ground. The thickness of the plate depends mainly on the mechanical resistance of each material.

It is also interesting to simulate wind conditions (31) (19). This will be done by performing experiments where the impact occurs obliquely to the plate.

3. Materials and Methods. -

3.1. Preliminary Tests. - The experiments reported in this section are a first approach to the technique, using different materials of interest for the plate. A square plate is taken as a reference shape. Its area is approximately 800 cm², its thickness is 8 mm. The diameter of the balls is d = [10; 15; 20; 25] mm. The aim is the plate center and the height is 1 m. Thus, $E_{ball}^{@impact} \in [40$ - 600] mJ. An electromagnet was used to assure null initial velocity and repetitiveness. The aim point is only changed for tests regarding the impact position. Only one piezoelectric receiver is used, fixed at $\left(\frac{1}{2}, \frac{1}{4}\right)$ of the plate, in normalized coordinates. The transducer is a piezoelectric diaphragm with a brass plate of 5 cm diameter and a ceramic element of 2.5 cm diameter and 0.2 mm thickness, with a resonant frequency of 3.2 kHz.

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.

Signals were digitized using an acquisition board (National Instruments NI USB6210) and a personal computer.

3.2. Design of the Hail-Impact Simulation Device. - The results of the preliminary tests showed the necessity to implement a calibration system. The built device (32) is formed by three main parts:

- Launcher-loader (Fig. IIIa)
- Base platform (Fig. IIIc)
- Elevator guide (Fig. IIId)

There are two launcher-loader instances. Each one consists of a loader, which holds balls and drops them one by one to the launcher. The launcher holds a single ball until commanded to drop it. The elevator guide and the corresponding motor control the drop height. The base platform holds the sensor.

The loader works by the same principle as the cylinder of a revolver. It is a hollow cylinder with eight partitions and a rotating floor (Fig. IIIb). Seven of the partitions are to hold one ball at a time, the other partition has a hole in the floor at the time of being loaded, so it must remain empty. The hole in the floor matches the shape and size of a partition. The floor turns around so that the hole advances one partition every time a ball is dropped to the launcher. The loader and the launcher are connected with ramps in a manner that softly guides the ball, not shown in the figure.

The launcher is a hollow cube without a 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 so that it is energized before moving the door, thus catching the steel ball and taking it to the drop position. When practicing single drops, the electromagnet is deenergized as soon as the drop position is reached. When doing double drops, both electromagnets are coordinated according to the delay requirements. Afterward, the doors return to their original position.

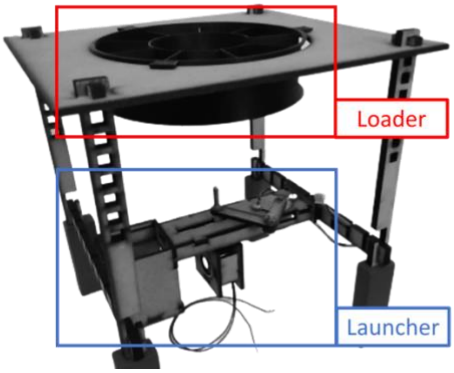
In the launcher-loader arrangement of Fig. IIIa, the loader is fixed meanwhile the launcher can be manually set into different positions by means of a dented ruler. This lets the user change the distance between the points where the quasi-simultaneous impacts strike.

The elevator guide consists of a 0.6 m × 0.4 m × 1.5 m aluminum structure with a stepper motor. The launcher-loader devices are hosted in two roller guides that serve as tracks for vertical movement. The vertical movement is operated by the motor, with a track length of 1 m. A pulley system aids the movement. In order to achieve some of the required heights, this structure will be hung on a wall.

The base platform is to be placed on the ground. It holds the sensor and some of the electronics of the system, being every part screwed to the base. It is heavy in order to give stability to the plate at the time of the impact. It also permits manual change of the zenith angle of the plate, for simulating the effect of wind in the hailstones. The angles can be changed from 0° to 45°, in 5° steps.

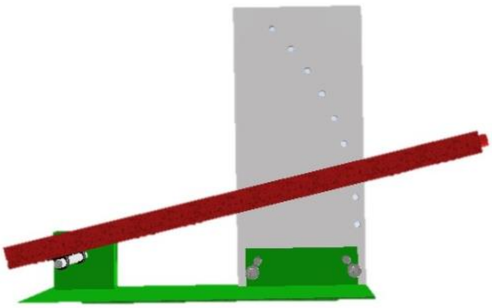
3.3. Application of the Constructed Device. - An experiment was performed with the constructed device with the objective of studying if a direct relation between two energies can be found: the energy transferred to a plate by the impact of a projectile E_{ball}^{tra} and the energy of a signal that can be acquired with a piezoelectric which is fixed to the plate, E_{signal}^{acq} . A constant k satisfying Eq. (5) was sought.

$$E_{ball}^{tra} = kE_{signal}^{acq} \tag{5}$$

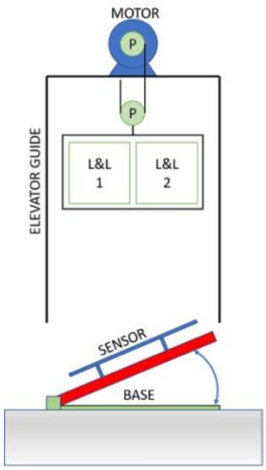


(a) Launcher and loader.

(b) Loader system.



(c) Base platform.



(d) Complete system.

Figure III. - Main mechanical parts of the SGran.

This experiment is realized in order to verify the feasibility of identifying E_{ball}^{tra} from the signal acquired with a piezoelectric transducer. The setup is as follows. The chosen plate is the acrylic one which was described in the *Preliminary Tests* section. The aiming point is the center of the plate. Balls of sizes [10; 15; 20; 25; 30] mm were dropped from a height of 1.5 m. The experiment was performed five times with each ball size. High-speed camera videos were made for measuring the bounce height and computing E_{ball}^{tra} as the difference between the energy of the ball at the drop E_{ball}^{drop} and the energy the ball conserves $E_{ball}^{conserved}$, as in Eq. (6).

$$E_{ball}^{tra} = E_{ball}^{drop} - E_{ball}^{conserved} \tag{6}$$

Observe that E_{ball}^{drop} is the same of Eq. (2), which equals E_{ball}^{impact}, of Eq. (3). For this experiment, it is recognized that only a part of the projectile energy is transferred to the measurement system.

For the final hail sensor, a calibration shall be performed, in order to relate the actually measured energy to the complete energy of the projectile at the time of impact. In the case of hail, the energy that is not transferred to the plate will mainly compound bouncing energy as well as braking energy, though some hailstones may not bounce or brake. The behavior will depend on the plate material as well as the composition of the hailstone, for which hypotheses will be necessary.

4. Results. -

4.1. Preliminary tests. - In Fig. IV, the signal when performing the explained experiment with a 25 mm ball impacting a stainless-steel square plate at the center is shown. The duration of the signal is in the order of milliseconds. The time between impact and the signal reaching its maximum is in the order of microseconds. After the maximum, the signal has a steep decay, which decelerates as a negative exponential. If useful information can be extracted from the beginning of the signal, the time between two impacts to be recognized as different ones shortens.

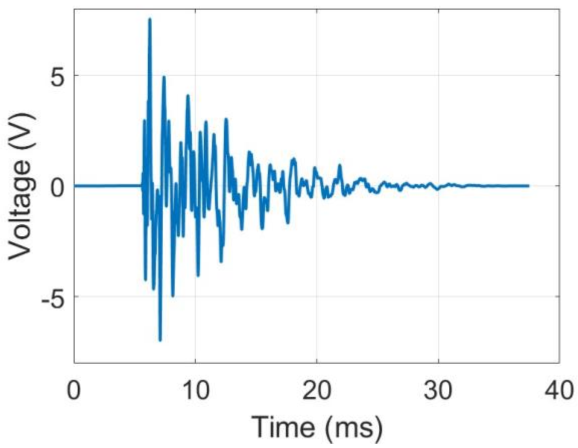


Figure IV. - Complete time signal.

Regarding repetitiveness, results show that the acquired signals are extremely similar if the experiment is thoroughly repeated. If the impact point changes, the signals change significantly. This is because the wave propagation paths are absolutely different.

Regarding energy, proportionality has been observed between the kinetic and the electrical for most of the materials. This is shown in Table I, where the energies are in percent since only proportionality is studied. The kinetic energy is calculated by using Eq. (2) and given as a percent. For each material, the mean percent energy obtained from the five repetitions at each point of the series is given. Every material is treated independently, the energies obtained with the biggest ball hitting each material is the reference for that material, corresponding to the 100% point. The energy recorded for every smaller ball is converted to the percent of its reference.

It is observed that when using either tempered glass, steel, or aluminum as the material for the plate, the bigger the ball, the higher it bounces. This relation is inverted when the plate is acrylic, resulting in higher bounces for smaller balls. This behavior is related to the transference of energy at the impact and is dependent on the elastic properties of the materials, particularly, the relation between the steel, used for the ball and the material of the plate. This observation lead to considering the energy conserved by the ball in the experiment performed as an application of the constructed device.

4.2. Tests with Constructed Device. - The constructed *SGran* presents an excellent repetitiveness. Fig. Va shows the first 2 ms time window of acquired signals for a set of repetitions.

The energy of the signal was computed, obtaining afterward the constant that best adjusts the model of Eq. (5) in terms of mean square error, k = 0.043. Note that this value is strongly dependent on the experimental setup and the signal processing decisions. Regarding experimental setup, plate material, shape, dimensions, piezoelectric transducer, and position of the transducer are

	Energy in % of that of the biggest ball.				
	Kinetic	Electric (with each plate material)			
d (mm)		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

Table I. - Results for the experiment on proportionality of energies.

Kinetic energy is calculated as the energy of a steel ball of known diameter in free fall for a known distance. Electric energy is computed from piezoelectric-transducer signals, which convert plate vibrations provoked by the ball impacting the plate at its center into voltages. Plates of different materials are tested. Energies are given as a percent of the biggest energy of each series.

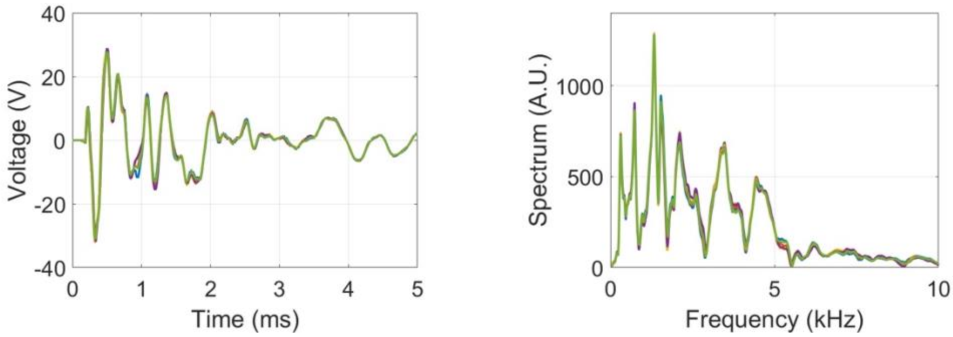


Figure V. - Results regarding five overlaid repetitions of the experiment.

Regarding signal processing decisions, significantly reducing the time window (for instance halving it) or reducing the frequency band for energy computation below 5 kHz would alter the results. If using a different setup, the same experiment shall be performed in order to obtain the corresponding constant.

The experimental results for the comparison of the energy transferred to the plate, E_{ball}^{tra} and the energy obtained from signal processing, E_{sig}^{acq} can be seen in Fig VI. E_{ball}^{tra} is computed as in Eq. (6), so the effect of bouncing does not influence the results. In the figure, E_{sig}^{acq} is multiplied by the obtained constant *k*, for showing the proximity of the points to the identity function. The dotted lines delimit the band where at least 50% of future observations would fall according to the linear adjustment.

5. Conclusions. - A device for automatic simulation of hail impact was designed and built in order to perform techniques based on the Energy Matching theory. The main purpose of this machine is to perform laboratory experiments that let us design and calibrate hail sensors.

Preliminary tests were performed to check the feasibility of the sensor concept. They showed a dependence between the energy of the signal and the kinetic energy of the balls in the studied kinetic energy range. It has been observed that some materials have better performance than others. In the test conditions, tempered glass, acrylic, and stainless steel present clear relations between kinetic and electric energies, whereas no relation is observed when using an aluminum plate.

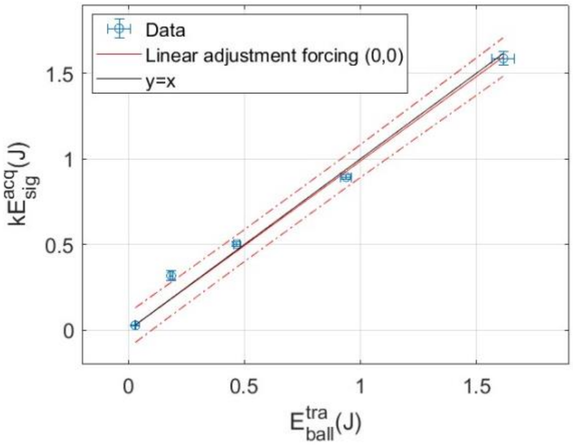


Figure VI. - Comparison of energy results. The linear adjustment is given with the band that will contain at least 50% of future observations.

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. The constructed device achieved excellent performance on repetitiveness: the variation in shape and amplitude of signals obtained when repeating experiments is almost negligible. It has shown to be a great aid for sensor development and calibration, which requires reproducing well-known impacts.

The results of the experiment performed with the constructed device are positive in order to continue with the intention of developing a hail sensor with an acoustic-electric principle.

In the chosen experimental setup, the energy of the acquired signals is proportional to the energy transferred to the plate. Then, it is possible to identify the energy transferred to the plate by the impact of a projectile from the signal acquired with a piezoelectric transducer. Nevertheless, more transducers would be necessary in case the restriction of the projectile impacting only at the center of the plate was withdrawn, in order to detect impact position by the technique of time of flight (33). In that case, a wider calibration would be required, compensating for the dependence on impact position.

In the immediate future, the experiment presented as an application of the constructed device will be repeated on plates of different materials. The next experiment is to check whether the tension with which the plates are screwed to the base affects or not the results. Then, an experiment will be conducted in order to observe if there are differences in the signals when different-sized balls impact the plate with the same energy. Therefore, the capability that the constructed device gives us of varying heights in a controlled manner while maintaining the impact point is essential.

After completing this basic experimental set, new procedures will be conducted for defining the characteristics of the plate. Afterward, we will thoroughly study the outcome of the plate for the chosen design. Particularly the energy of the acquired electrical signals, regarding certain inputs of interest: the relation between the energy of measurements and kinetic energy at the time of impact, the 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, as a part of the sensor development.

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2. Adquisición de datos
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4. Discusión de los resultados
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