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Transactional engineering for green airports maximizing taxiing energy recovering case

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Abstract

This work explores the KERPS system (Kinetic Energy Recovery by Pressure on Slabs) as a solution for harnessing kinetic energy from aircraft taxiing. By embedding piezoelectric slabs in airport runways and taxiways, the system aims to convert aircraft-induced mechanical vibrations into electrical energy, enhancing airport sustainability and reducing reliance on conventional power sources, in line with COP recommendations on energy transition and carbon footprint reduction. Using MATLAB and COMSOL Multiphysics, this study analyzes the interaction between a Boeing 747's landing gear and the piezoelectric slabs, considering key parameters such as mass, velocity, damping, and resonant frequency. Simulations indicate that an empty Boeing 747 can generate up to 55 kW, while a fully loaded aircraft produces approximately 53 kW. To optimize energy use, a lithium battery storage system is proposed for energy retention and redistribution. By aligning the resonance frequency of the slabs with aircraft-induced vibrations, the system improves energy conversion efficiency, making self-sufficient airports a viable reality. This study supports the adoption of KERPS technology to power airport infrastructure while meeting the requirements of engineering firms and energy auditors seeking sustainable, high-performance solutions, fully aligned with global commitments to sustainability and carbon neutrality.

Keywords: Damper, Energy harvesting, Frequency, Innovation, Kinetic energy recovery, Piezoelectric, Renewable energy, Sustainability, Sustainable airport infrastructure.

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1. Introduction

The mass-spring-damper piezoelectric platform (MSD-PP) is an innovative technology gaining increasing attention, particularly in the field of airport engineering. Unlike traditional applications of piezoelectric energy harvesting, this study focuses on a unique and unexplored approach: the use of slabs placed on airport runways and taxiways to generate electricity from the vibrations caused by the passage of aircraft. These slabs, equipped with piezoelectric materials such as PZT (Lead Zirconate Titanate), convert mechanical energy from vibrations into electrical energy [1-3].

This novel system is based on mass slabs attached to springs and dampers, which undergo oscillatory motion when an external force, such as an aircraft passing by, is applied. The PZT material then generates an electrical potential through the piezoelectric effect [4] which can be harnessed to power airport infrastructure, contributing to the airport's self-consumption of energy. This conversion process is crucial in environments like airports, where vibrations are constant, and energy demand is high.

Optimizing the MSD-PP platform is essential for maximizing its energy recovery efficiency. Recent advancements in energy harvesting technologies have demonstrated the effectiveness of automated design flows, such as those based on HDL software platforms, which can improve energy harvesting efficiency by up to 75% through precise modelling and optimization [5]. In our study, we employ scientific simulation tools like MATLAB and COMSOL [6]. These tools allow for the modelling and analysis of the system's physical behavior by adjusting key parameters, such as the resonant frequency. The resonant frequency is determined by the mechanical properties of the system, including the mass of the slabs, the springs, and the dampers, and plays a pivotal role in ensuring the system operates at peak energy conversion efficiency. Fine-tuning this frequency is critical to enhancing the platform's ability to generate electricity from the vibrations induced by aircraft passage.

In this context, the MSD-PP solution offers significant advantages as a clean and renewable energy source. Airports, due to their high traffic and constant vibrations generated by aircraft and other mechanical systems, provide an ideal environment for implementing such technology. By harvesting energy from the vibrations of aircraft, this approach enables airports to reduce their dependence on external energy sources, promoting energy autonomy. The integration of simulation tools like MATLAB and COMSOL in the optimization process ensures precise control over the system's parameters, maximizing energy output for practical use [7].

In summary, our study presents an innovative and unexplored technology for energy recovery in airport infrastructure, converting aircraft-induced vibrations into electricity for self-consumption. By using simulation tools to model and optimize key parameters like resonant frequency, the platform can be tailored to achieve maximum energy recovery, providing a sustainable solution for airports' energy self-sufficiency [6].

2. Nomenclature

2.1. Variables and Functions

F: Force exerted on the slab,
m: Airplane weight,
a: Airplane acceleration at the time of passage,
x: Slab deformation,
k: Slab stiffness constant,
ρ: Material density,
u: Displacement of the PZT piezoelectric structure,
σ: Stress tensor,
f: Force density,
∇: Nabla operator.

2.2. Abbreviations

PZT: Lead Zirconium Titanate,
MSD: Mass-Spring-Damper,
PP: Piezoelectric Platform,
LG: Landing Gear,
PPE: Public Place Equipment,
B747: Boeing 747 aircraft,
ICAO: International Civil Aviation Organization,
KERPS: Kinetic Energy Recovery by Pressure Slabs,
EPR: Electrical Power Recovered.

3. Problem Formulation

3.1. Data collection

3.1.1. Bejaia Terms Airport

Bejaia International Civil Airport (Figure 1) is a prominent international airport located at sea level Table 1, with an elevation of 0.0 m, covering an area of 20,000 m². The airport, constructed using asphalt concrete and incorporating KERPS (Kinetic Energy Recovery by Pressure on Slabs) technology, complies with the standards and regulations set by the International Civil Aviation Organization (ICAO) [8]. The airport's infrastructure, including its runways and terminal areas, is designed to maintain high safety standards and operational efficiency.

We selected this airport as a case study for our energy modernization initiative for several reasons. As part of our research, we conducted a comprehensive technical study of the airport's energy consumption, focusing particularly on the aerodrome lighting system. The study revealed that the airport's lighting infrastructure, consisting of 800 light fixtures, each with a capacity of 150 watts, could be effectively powered by our innovative energy recovery solution using pressure-generating slabs. This solution has the potential to significantly reduce the airport's reliance on traditional energy sources, contributing to a more sustainable and energy-efficient operation.

Figure 1.
KERPS visualization scene with X-plane [9].

Table 1.
Geographical coordinates and average altitude sea level [9].

Latitude: 36°33′00.00″ North.
Longitude: 4°42′00.00″ East.
Altitude: 6 m above sea level
The current runway is 2,500 m long and 45 m wide

For this study, our proposed solution involves the installation of a Mass-Spring-Damper piezoelectric (MSD) system, specifically designed for the collection of kinetic energy. This concept is based on a patented energy generation device that integrates electro-active slabs into walkways or roads [10]; these slabs capture and convert the kinetic energy from pedestrian or vehicular movement into electrical power. The principle behind this technology ensures efficient energy harvesting in high-traffic areas, making it a viable solution for sustainable power generation [11].

The slabs themselves are supported by springs, and as pedestrians or vehicles pass over them, the energy generated from the footsteps, or the weight of the vehicles is captured. Each slab is equipped with a mini generator placed beneath it, which converts the mechanical impact into electric current. This electrical energy is then stored in a connected battery, which can be used to power various devices, such as LED lamps installed along the walkway. To optimize energy conversion, a positive output voltage-lift Boost converter is employed, offering a higher voltage transformation ratio and reduced voltage stress across semiconductors. An additional inductor enhances efficiency, and the converter's dimensioning, dynamic behavior, inrush-current management, and feed-forward control are refined through simulations [12]. This creates an environmentally sustainable method of energy generation, particularly useful for outdoor lighting in areas with high foot traffic or vehicle movement. As an illustrative example, it has been estimated by Villerouge [10] that with 10,000 pedestrian crossings during the day, this system could provide up to 3 hours of free lighting [11].

The energy output per pedestrian is approximately 4 to 6 watts per step, depending on the individual's pace and weight. This makes the MSD system a reliable and efficient energy harvester in urban environments. Based on the patent's specifications, each slab is estimated to generate 5 watts for every pedestrian crossing [11].

To scale this solution to an airport environment, we recommend deploying the same system with 5,000 slabs installed on each side of the Boeing 747's two main landing gear tracks—left and right—resulting in a total of 10,000 slabs. The Boeing 747 was selected for this study due to its configuration, which includes four main landing gear assemblies, each consisting of four wheels, for a total of 16 wheels rolling across the slabs [8]. The slabs used will be one meter long, ensuring they are appropriately sized for the aircraft's wheels and providing an optimal fit for the mechanical calculations required.

The configuration of the B747's landing gear is particularly suitable for this application because its multiple wheels ensure that the slabs will experience regular and consistent mechanical stress Figure 2.

This allows for a predictable and consistent energy generation rate, making the deployment of the MSD system at high-traffic zones of the airport not only feasible but also scalable for larger applications. By adapting this system for use on an airport runway or taxiway, the energy generated from each aircraft's movement could be used to power airport infrastructure, such as runway lighting, digital displays, or other essential systems, contributing to the airport's sustainability goals and reducing its reliance on external power sources.

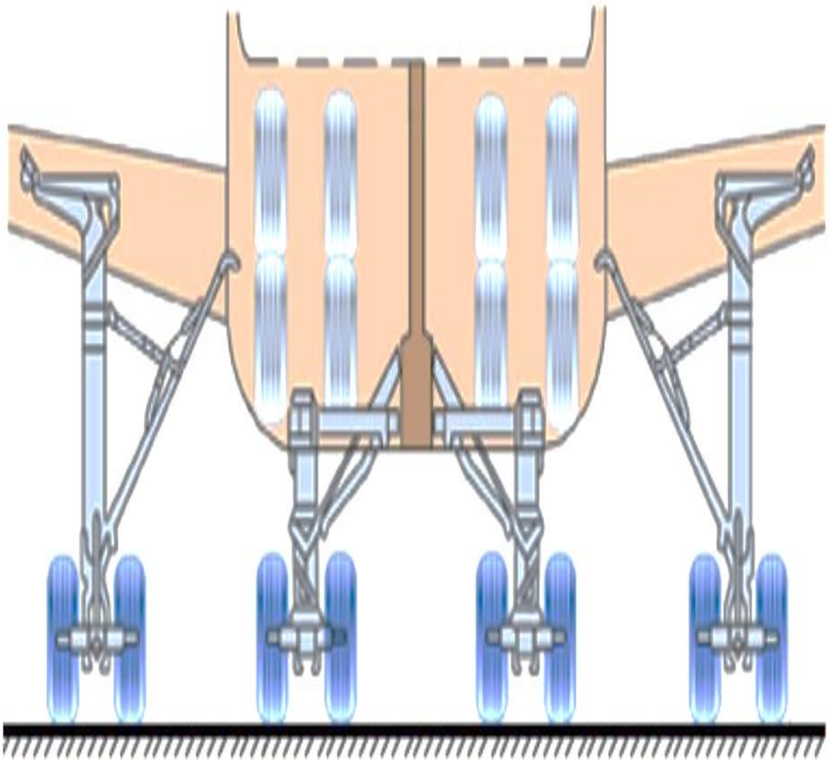

Figure 2.
B747 main LG seen from the rear [8].

3.2. Mechanical Constraint at the Moment of Passage on a Podo-Electric Slab

To accurately analyze the energy conversion potential of the Mass-Spring-Damper (MSD) piezoelectric system, we begin by modelling the Landing Gear (LG) at the precise point of contact with the KERPS surface. This modelling allows us to systematically assess the mechanical forces exerted during landing and taxiing, which generate the PZT piezoelectric effect. The dynamic interaction between the landing gear wheels and the slabs is critical, as the distribution of forces directly influences the efficiency of the energy harvesting system.

As shown in Figure 3, the landing load volume exerts significant support forces on the slabs, which must be carefully considered to optimize the piezoelectric energy conversion process. A 2D mechanical model has been developed to represent the loading conditions of the landing gear on a slab, capturing the key parameters contributing to force generation. Our primary focus in this analysis is on the bearing force exerted on the concrete slab, as this is the key parameter that activates the PZT piezoelectric effect.

The landing gear system of a large aircraft, such as the Boeing 747, generates substantial dynamic loads as it moves across the slabs. The vertical forces experienced by the MSD slabs depend on several factors, including:

- Aircraft weight: The Boeing 747, for example, has a maximum landing weight of approximately 295,742 kg [13].
- Speed of impact: The forces vary based on whether the aircraft is landing, taxiing, or stationary.
- Impact speed: The forces vary depending on whether the aircraft is landing, taxiing, or stationary.
- Landing gear configuration: The aircraft's four main landing gear assemblies, each with four wheels, distribute the weight and force across multiple contact points.
- Slab elasticity and damping: The mechanical properties of the KERPS concrete and the spring-damper system influence how force is transmitted and absorbed.

By integrating these factors into our model, we ensure a precise and realistic simulation of the mechanical forces acting on the piezoelectric slabs. The primary objective of this analysis is to optimize the resonant frequency and mechanical response of the slabs, ultimately enhancing energy output. This optimization will contribute to the system's effectiveness in large-scale airport applications.

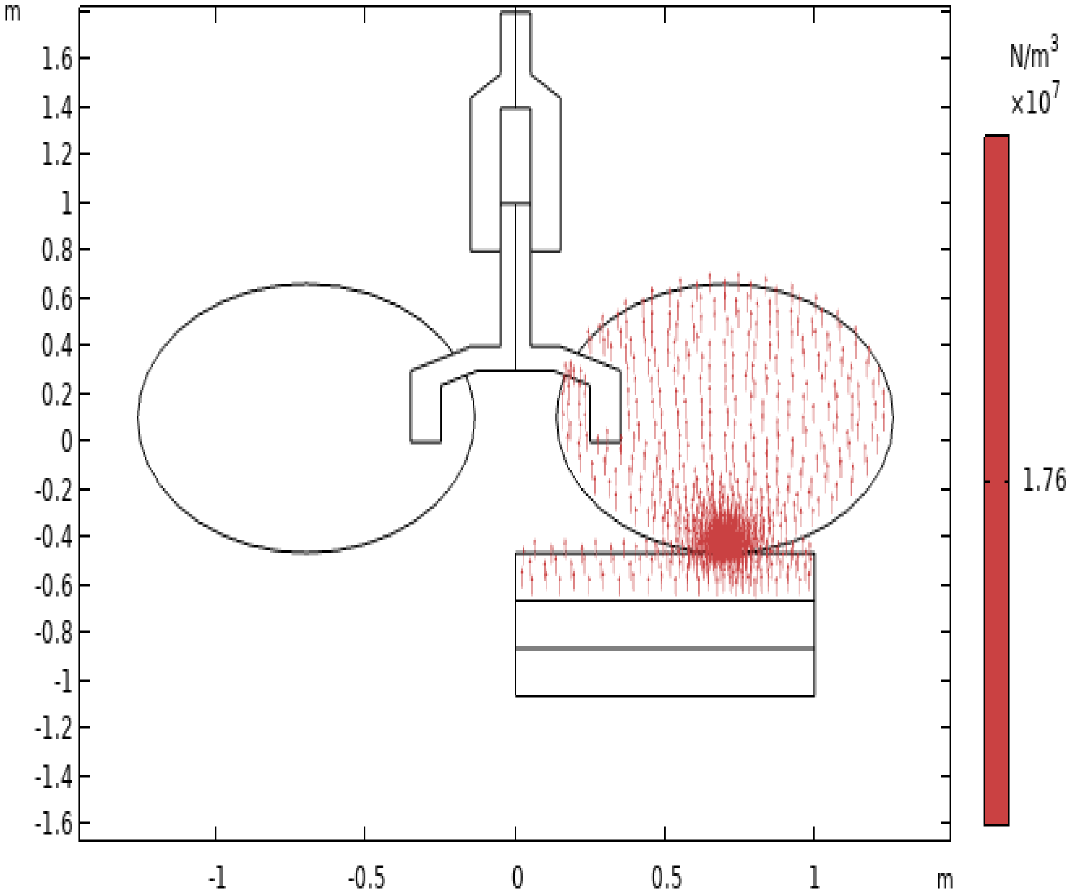

Figure 3.
Volume loading of the LG of a B747 airplane on a concrete KERPS/Slab.

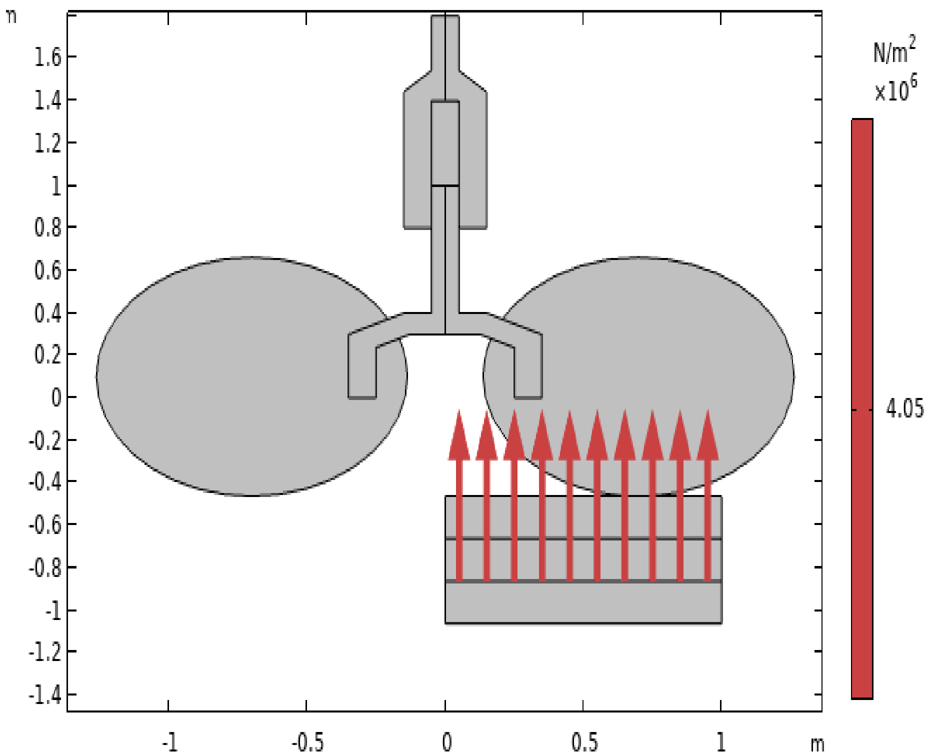

Figure 4.
Surface loading of the LG of a B747 airplane on a concrete KERPS/Slab

The combined mass of two airplanes crossing the KERPS system, which consists of multiple podo-electric slabs, generates mechanical forces that are converted into electrical energy. This energy harvesting process is simulated using COMSOL Multiphysics software, integrating the PZT piezoelectric and electromechanical modules to analyze the system's performance. However, these forces not only facilitate energy harvesting but also induce mechanical stresses, vibrations, and shear deformations in the slabs.

To evaluate these mechanical constraints, COMSOL Multiphysics simulations are employed to identify high-stress concentration zones, as illustrated in Figure 4. These simulations provide a detailed analysis of stress distribution, ensuring that the slabs can withstand the forces exerted by a Boeing 747 without structural failure. To ensure durability and mechanical stability, our slabs are engineered for high robustness as in Jian, et al. [14] utilizing reinforced concrete due to their superior compressive strength and fatigue resistance.

Our study focuses specifically on the energy harvesting technique by analyzing the mechanical behavior of the slabs under real operational conditions. By optimizing their structural response and energy conversion efficiency, we aim to develop a reliable and scalable solution for sustainable energy generation in airport environments.

The maximum normal stress σ_{max} exerted on the slab can be expressed using the following equation:

$$\sigma_{max} = F / A + (M * y) / I \qquad (1)$$

where:

F is the applied force from the aircraft wheels,

A is the cross-sectional area of the slab,

M is the bending moment induced by the applied load,y is the perpendicular distance from the neutral axis to the point of interest,

I is the moment of inertia of the slab’s cross-section.

Additionally, the electromechanical behavior of the PZT piezoelectric material is governed by the following equation:

$$D = d_{33} * \sigma + \varepsilon_{33} * E \qquad (2)$$

where:

D represents the electric displacement,

d_{33} is the piezoelectric coefficient,

σ is the mechanical stress applied to the material,

ε_{33} denotes the dielectric permittivity,

E is the induced electric field.

By incorporating these mathematical models (1) and (2), the study ensures a comprehensive understanding of the mechanical and electrical behavior of the system, optimizing the slab design to maximize energy harvesting while maintaining structural integrity.

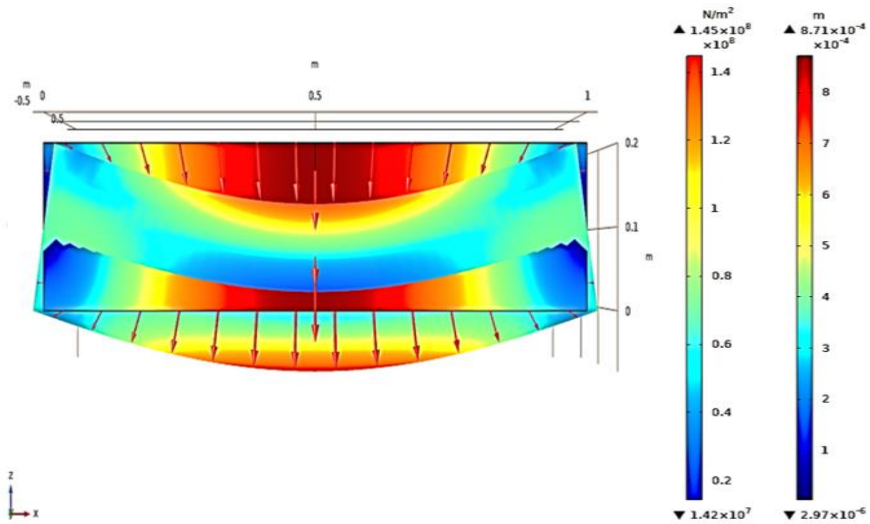

Figure 5.
3D representation: Von Mises Stress-Volume: displacement amplitude-arrow: displacement field.

When an external force is applied to the slab, it undergoes deformation, generating mechanical vibrations [15]. These vibrations can be effectively harnessed and converted into electrical energy through PZT piezoelectric technology [16]. The fundamental relationship between applied force and resulting displacement is governed by Hooke's law, which states that the restoring force exerted by an elastic material is proportional to its displacement:

$$F=K*X \qquad (3)$$

Where:

is the applied force,

is the deformation of the slab,

is the stiffness constant of the slab.

This equation establishes that the force exerted on the slab is directly proportional to its deformation, with the stiffness constant k determining the material’s resistance to displacement. The integration of this relationship (3) into vibration analysis allows us to express the link between the dynamic force and the resulting oscillations.

The equation of motion for a mass-spring-damper system is given by:

$m\ddot{x}+c\dot{x}+kx=F(t)$ (4)

where:

m is the effective mass of the slab,

c is the damping coefficient,

k is the stiffness constant,

x represents displacement,

$\dot{x}$ and $\ddot{x}$ denote velocity and acceleration, respectively,

F(t) is the applied dynamic force.

If damping is neglected (c=0) in (4), the equation simplifies to:

$m\ddot{x}+kx=F(t))$ (5)

Assuming the applied force from the aircraft follows a harmonic excitation:

$F(t)=F_0*\cos(\omega t))$ (6)

where:

F_0 is the amplitude of the applied force,

ω is the excitation frequency caused by the aircraft movement.

The resulting vibrational response of the system can be expressed from (6) as:

$x(t)=X*\cos(\omega t-\phi)$ (7)

where:

X is the displacement amplitude,

ϕ represents the phase shift introduced by the system.

The displacement amplitude X of the slab's oscillation is obtained by substituting F0 from Equation 6 into Equation 7 resulting in the following expression:

$X=F_0/k-m\omega^2$ (8)

This Equation 8 highlights that the slab's vibrational response is directly influenced by the aircraft's excitation frequency and the natural frequency of the slab, given by:

$\omega n=\sqrt{k/m}$ (9)

This demonstrates that the force applied by the aircraft, particularly a Boeing 747, induces a proportional deformation in the slab. The mechanical response of the slab leads to oscillations, which, through the piezoelectric effect, can be converted into usable electrical energy [7]. The slab's vibrational behavior is also influenced by its natural frequency, given by Equation 9; This relationship shows that when the excitation frequency of the aircraft approaches ωn, resonance occurs, leading to amplified oscillations and increased energy conversion efficiency.

4. Problem Solution

4.1. First Case: Comparison of Pedestrian and Aircraft Interaction with the Slabs

For the first simulation, a comparative analysis is performed between a pedestrian and an aircraft traversing the slab system. A MATLAB-based simulation was developed to estimate the energy harvested from their respective movements. This simulation calculates the force applied to the slabs, neglecting vibrational damping effects. Figure 5 illustrates the electrical power output generated by both cases within the same simulation window Figure 6.

Despite sharing the same fundamental pressure mechanism, the extent of slab interaction differs significantly. A pedestrian, due to spatial constraints, only engages with a fraction of the slabs—approximately one-quarter (1/4) of the total available area. In contrast, the Boeing 747, with its four landing gear (LG) assemblies, traverses the entire slab system, applying a much greater force, thus enhancing the energy generation potential.

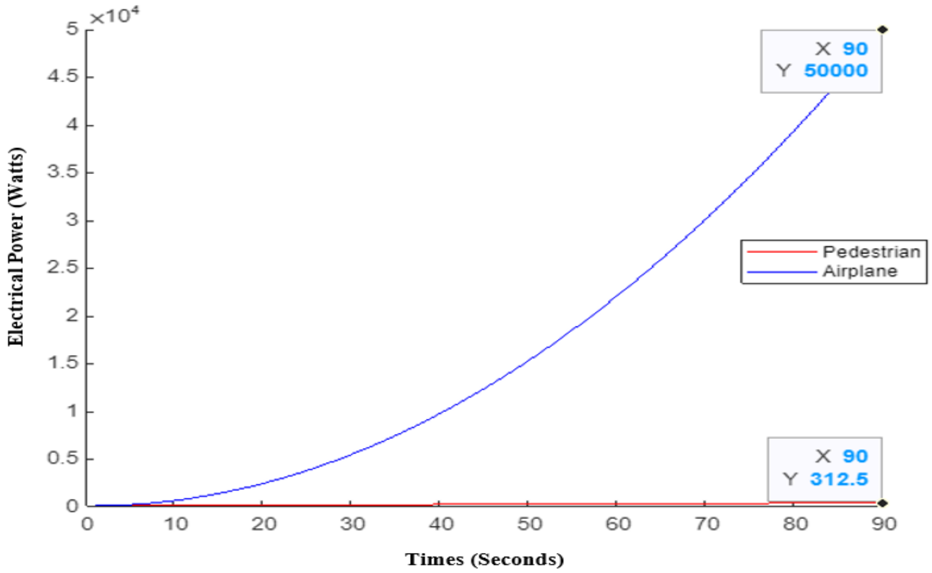

Figure 6.
Total power recovered by the simple passage without considering the vibrations.

4.2. Second Case: Empty and Loaded Aircraft Behavior on Runway Slabs

This case focuses on utilizing the vibrations of the slabs to harvest energy. To model this behavior, we use Navier's equation, which defines the mechanical behavior of the PZT piezoelectric slab under the forces exerted by the B747. This equation represents the relationship between the stresses, strains, and elastic properties of the PZT piezoelectric material. The Navier equation for a PZT piezoelectric material is as follows Navier's Equation:

$$\rho u=\nabla\cdot(\sigma)+f \quad (10)$$

Where:
P is the material density
u is the displacement of the PZT piezoelectric structure
σ is the stress tensor
f represents the force density
∇ is the nabla operator

In this study, the stresses and vibrations caused by the passing aircraft over the PZT piezoelectric slab are calculated using this Equation 10. The mass of each B747, as well as its cargo, are taken into account. For an empty B747, only the aircraft's mass is considered, while for a fully loaded B747, the additional cargo mass is factored in. The force density, denoted as f, is calculated based on the masses of the system.

This model calculates the resulting vibrations caused by the B747s. The physical equation used to model the vibrations of the slabs, due to the airplane's landing, is based on the Navier-Cauchy equation, which describes the propagation of elastic waves through an elastic medium. Since the soil beneath the slabs is elastic, the slabs are modelled as having a spring beneath them to account for vertical deformation under pressure. The pressure exerted by the aircraft's weight is then converted into electrical charge by the PZT piezoelectric slabs, generating electrical energy.

This formulation allows the energy generation potential to be determined from the mechanical interactions between the B747 and the slab system.

4.2.1 Initial Programming Data

m_1=183500kg, m_2=412769kg masses of B747 1 and 2, respectively.
k=4038508.2N/m stiffness constant of the MSD system for m_2
c damping factor of the MSD system.
u(t): displacement of the MSD system at time t.
u′(t): displacement speed at time t
u″(t): displacement acceleration at time
F(t): force exerted on the MSD system by the B747 at time t

4.2.2. Initial Conditions

The B747 has a landing speed of 70 m/s, which is ideal for better navigation, and there will be braking until the speed reaches zero.
u (0) =u0=0.5 m (initial displacement).
u′ (0) =v0=70 m/s (initial speed).

4.2.3. Simulation Duration

The simulation runs for a total duration of 90 seconds, with a time step of 0.01 seconds to ensure high precision in the results

The following initial programming data are proposed to configure and launch the simulation in MATLAB:
m_1 = 183500 kg, m_2 = 412769 kg: masses of B747 1 and 2 respectively
k = 4038508.2 N/m: stiffness constant of the MSD system maximum for m2
c: damping factor of the MSD system
u (t): displacement of the MSD system at time t
u'(t): displacement speed of the MSD system at time t
u"(t): displacement acceleration of the MSD system at time t
F(t): force exerted on the MSD system by the B747 at time t

The initial conditions are assumed in the case of landing; the landing B747 has a speed of 70m/s recommended for better navigation; and there will be braking until zero speed is reached:
u (0) = u0 = 0.5 m (initial displacement)
u'(0) = v0 = 70 m/s (initial speed)

The total duration of the simulation is tf = 90 s, with a time step of 0.01 s.

Now, a MATLAB program is used to calculate the total power recovered for each airplane scenario. Figure 7 shows the results of the electrical power recovered from the landing of two B747 aircraft (empty and fully loaded) over the KERPS system, consisting of piezoelectric slabs under the same damping conditions. Using the vibrations as a measure of mass, we can calculate how much electrical power is harvested.

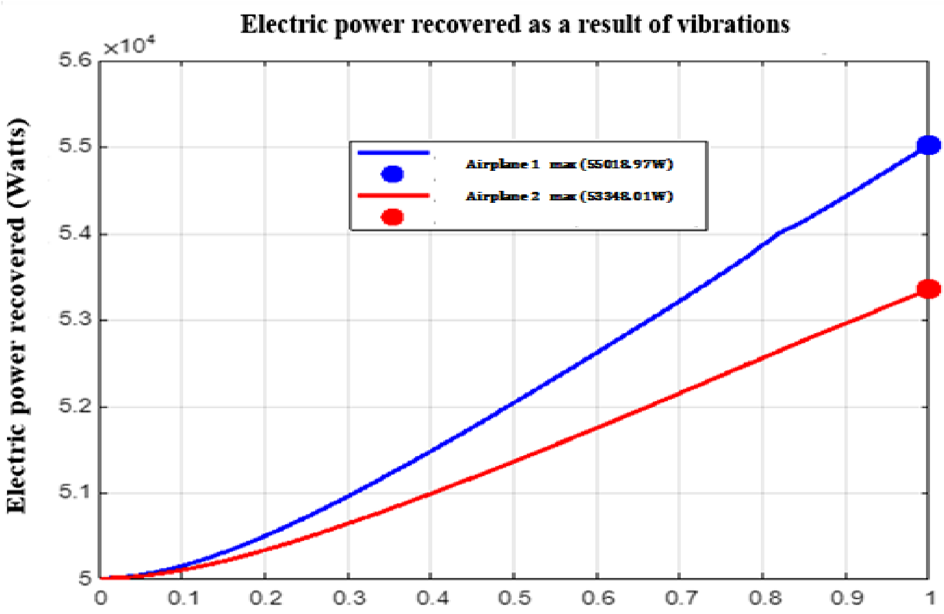

Figure 7.
Total power recovered by the simple passage without considering the vibrations

The results of the MATLAB code can be seen in Figure 7.

The calculation was performed by multiplying the initial vibration power by 10,000 slabs. Afterward, the total power generated by the vibrations was summed, considering the maximum number of vibrations.

For the first airplane, the weight/psi combination that allows for the maximum electrical power recovery is:

- Weight = 183500 kg
- Psi = 1.00
- EPR = 55018.97 W

For the second airplane, the weight/psi combination that results in the maximum electrical power recovery is:

- Weight = 412769 kg
- Psi = 1.00
- EPR = 53349.01 W

When a PZT piezoelectric slab reaches its pressure limit, energy production is no longer proportional to the force applied. This explains why the lighter airplane recovers more electrical energy than the heavier one. The lighter airplane, with its lower mass, exerts less force on the slab, but generates a larger vibration amplitude. Therefore, the lighter aircraft will produce more energy than a heavier B747 while landing on a PZT surface.

This observation can be interpreted in several ways:

Firstly, even if all other conditions remain the same, the system's dynamic response may vary depending on the B747's weight. We believe that lighter aircraft may have a higher vibrational frequency, which is closer to the system's resonance frequency Figure 8. This results in a higher vibration amplitude, which in turn produces more energy. This phenomenon is referred to as the "vibration quality."

The resonant frequency is determined by the system's physical properties, such as stiffness (k) and mass (m). The formula for the resonant frequency (f_0) is as follows:

f=1/(2*pi) *sqrt(k/m) (11)

Where f is the resonance frequency in Hz, k is the spring rate constant in N/m, and m is the mass in kg.

This formula (11) was used to calculate the resonant frequency of more complex systems by considering the characteristics of each element of the system. The higher the resonant frequency, the greater the amplitude of the vibrations, which will generate more electrical power.

Synthesis:

The relationship between the Electrical Power Recovery (EPR), the resonance frequency, and the number of vibrations is encapsulated in the following equation.

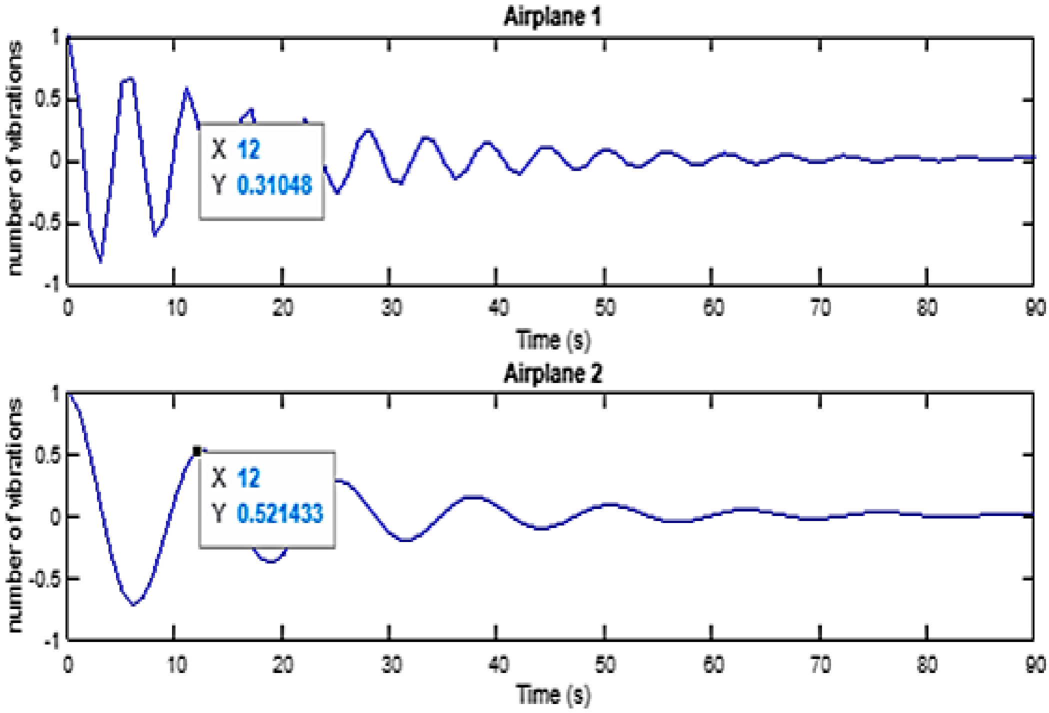

Figure 8.
Plot of the number of vibrations versus landing time.

The mathematical formula of this equation is:

$$P=k*f^3*A^2*N \tag{12}$$

With:
P represents the EPR
k is a proportionality constant
is the resonant frequency
A is the vibration amplitude
N is the number of vibrations.

This formula reveals that the electrical power recovery is directly proportional to the cubic power of the resonance frequency (f^3), the square of the vibration amplitude (A^2), and the number of vibrations (N).

Essentially, the higher the resonant frequency, the more effective the system is at amplifying vibrational energy, thus improving the overall power recovery. Similarly, a larger amplitude or a higher number of vibrations leads to more significant energy harvesting. Consequently, optimizing these parameters is crucial for maximizing the system's efficiency, particularly when considering the varying weight and load conditions of the passing airplanes. This equation serves as a foundational model in understanding how different physical variables contribute to the energy harvesting capabilities of the PZT piezoelectric slabs in the runway system and highlights the importance of tuning the system to resonate at frequencies that maximize energy conversion.

5. Conclusion

This study demonstrates the potential of harvesting electrical power through the alignment of vibration frequencies with the resonance frequency of PZT piezoelectric slabs, particularly in relation to the mass of the airplane. The findings reveal that the Electrical Power Recovery (EPR) of 55 kW for an empty Boeing 747 and 53 kW for a fully loaded one directly addresses the energy demands of Béjaïa Airport. For instance, the aerodrome lighting system—consuming 120 kW for 800 lamps—can be fully powered by the simultaneous passage of two aircraft over the KERPS slabs, with surplus energy stored in lithium batteries for later use [17]. This demonstrates the feasibility of replacing conventional energy sources with self-generated, vibration-derived power, significantly reducing the airport's carbon footprint.

The analysis extends to include the damping effects and the attenuation of amplitude following the passage of the airplane, as well as the adaptable actuation intervals for the Mass-Spring-Damper (MSD) system. In the context of combating climate change and reducing greenhouse gas emissions, the use of PZT piezoelectric slabs to recover electrical energy in airports represents a promising innovation for converting mechanical energy into electrical power. This technology leverages the PZT piezoelectric effect, where materials generate electricity under mechanical stress, such as the vibrations caused by the movement of airplanes across airport runways (KERPS).

The Electrical Power Recovery (EPR) is influenced by several key factors, including the weight of the B747, the resonance frequency, and the amplitude of vibrations. The resonance frequency plays a critical role, as it corresponds to the natural frequencies of vibration of the PZT piezoelectric slabs. This alignment between the slab's vibrational frequency and that of the passing airplane enhances the efficiency of energy harvesting. When the frequencies are in close proximity, the system can harness more energy, demonstrating the importance of optimizing resonance conditions for maximum energy conversion.

Given that this technology allows for the recovery of electrical energy from a non-electric, pollutant-emitting source, its integration into the design of KERPS for landings and takeoffs should be considered within airport engineering practices. It is essential, however, to ensure that this approach aligns with stringent safety and efficiency standards set by regulatory bodies, such as the International Civil Aviation Organization (ICAO). While reducing environmental impacts, it is imperative that innovations in this sector are carefully implemented to ensure the continued safety and reliability of air travel.

One potential avenue for enhancing energy recovery is the use of automobile springs to decouple the PZT piezoelectric slab from the concrete slab beneath. This approach could amplify the vibration amplitude, thereby increasing the amount of energy harvested. However, it is crucial to evaluate the properties of the springs to ensure they are compatible with the PZT piezoelectric material and compliant with safety regulations. The case study parameters provide a useful foundation for evaluating the feasibility of this approach.

The PZT piezoelectric action in slabs is an innovative means of generating clean, renewable energy within the airport industry. By combining this technology with springs, we can optimize energy harvesting. Moving forward, further research into this technology is essential to improve the efficiency of green energy production, reduce the carbon footprint of the aviation sector, and align with the COP recommendations for climate change mitigation.

For future work, the simulation framework used to calculate the power generated by this system also includes a decision support tool to assess whether the investment is economically viable for the city. This analysis is based on various criteria that will be detailed in subsequent studies, emphasizing the need to make infrastructure both energy-efficient and financially sustainable. Future efforts should incorporate transdisciplinary engineering design within engineering offices for the eco-design of public infrastructure, ensuring that sustainability and energy self-sufficiency are prioritized in the development of urban and transportation systems. Advanced tools for material selection [18] can play a crucial role in optimizing the design of energy harvesting systems, further enhancing their efficiency, sustainability, and scalability, particularly in high-traffic environments like airports.

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