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Ambient Vibration Energy Harvesting for Vehicle Suspension System

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***Abstract*— The push for sustainable and energy-efficient automotive technologies has led to a surge in interest in harvesting ambient vibration energy from vehicle suspension systems. In a conventional suspension system, all of the vibrational energy is turned into heat, so a lot of energy is lost in normal vehicle operation. To overcome this problem, in this work an electromagnetic vibration energy harvester is considered, which is designed to convert oscillatory motion into usable electrical power. The system is comprised of a moving N52 neodymium magnet assembly and stationary copper coils. Faraday's law of electromagnetic induction is applied to this setup to generate alternating voltage. An AC voltage is rectified by a Schottky diode bridge and stored in a bank of super capacitors for efficient energy buffering. The stored energy is regulated to a stable 12 V output for driving low-consumption automotive using a DC–DC boost converter. Experimental results show that the system is able to produce about 1.16 W per unit of suspension at typical vibration frequencies. The energy harvested is enough to power sensors, monitoring modules and microcontrollers without drawing power from the main electrical system of the vehicle. The proposed design improves the energy utilization in the vehicle while reducing dependence on batteries or alternators. This work generally confirms the feasibility of vibration-based energy harvesting as an environment friendly approach to improve electrical efficiency of modern automotive systems.**

***Keywords*— Ambient Vibration Energy Harvesting (AVEH), Vehicle Suspension Systems, Energy-efficient automotive technologies, Electromagnetic vibration-energy harvester, N52 neodymium magnet assembly.**

I. INTRODUCTION

The fast worldwide conversion to sustainable and energy-efficient transportation has raised the demand for discovering and utilizing alternative renewable energy sources within the vehicles. Electrical subsystems such as battery-management units, sensor networks, control electronics, communication modules, and infotainment systems are heavily relied on in modern electric and hybrid vehicles [1]. These increasing electrical demands onboard add load to the primary energy source, reducing overall efficiency and driving range. On the other hand, the traditional suspension systems in vehicles are constantly subjected to vertical oscillations due to uneven road surfaces, acceleration, braking and dynamic load variations [2]. It is well known that these vibrations contain a large amount of mechanical energy. However, conventional shock absorbers convert almost all of this energy into heat, and there is a huge reserve of energy that can be recovered by the suspension system [3].

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A promising strategy to recover this lost vibrational energy is to convert it into usable electrical power using Ambient Vibration Energy Harvesting (AVEH) [4]. Among different energy harvesting mechanisms such as piezoelectric, electrostatic, hydraulic and electromagnetic, the electromagnetic energy harvesting has been found to be particularly effective in the low-frequency high-amplitude vibrations such as those found in vehicle suspensions [5].

The relative motion of a magnetic core and a multi-turn copper coil produce an alternating voltage that can be processed into regulated DC power, according to Faraday’s Law of Electromagnetic Induction. This makes electromagnetic harvesters an attractive passive and rugged solution for automotive environment where reliability, minimum maintenance and long operational life are critical [6].

There are other reasons for use of AVEH in vehicles than just energy recycling. Small amounts of power can be successfully harvested from suspension vibrations to power distributed low-power loads such as wireless IoT sensors, tire-pressure monitoring systems (TPMS), microcontrollers and indicator modules. In electric vehicles, where every watt saved adds to the range, the use of small-scale regenerative modules in the suspension system can significantly improve the overall energy profile of the vehicle. Besides, the advancement of intelligent transportation systems has raised the need for self-powered sensors capable of operation without the main battery [7].

This work is devoted to the design and development of an electromagnetic vibration- energy harvester based on a linear moving-magnet and stationery-coil architecture [8]. The system backbone [9] comprises high-strength N52 neodymium magnets, precision-wound copper coils, a Schottky-based rectification stage, supercapacitor-based energy storage and a DC–DC boost converter. The aim is to experimentally demonstrate the feasibility of harvesting vibration-based energy from vehicle suspensions and providing regulated power for low-energy applications. This project demonstrates the systematic analysis, implementation and testing of the wasted ambient vibrational energy to generate a meaningful and sustainable power source for modern automotive electronics [10].

II. Problem Statement

A. Suspension Systems waste energy

Conventional combustion-engine vehicles use mechanical shock absorbers and mechanical springs in their suspension systems to absorb shocks and vibrations from the road. The excess vibrational energy present at the time of vibration will be totally discarded as heat and not used by the vehicle, thus producing an energy loss from an unused or wasted source of operational energy to be collected at each time you take the vehicle on a trip.

B. Absence of Energy Recovery Systems

Most suspension components on cars do not have any recovery system that captures energy produced while driving vertically (due primarily to the suspension system being an energy-producing device). Because of this, there's a significant opportunity to harvest energy from the vehicle's suspension system.

C. Rising Demand for Electrical Energy in Vehicles

Electric/hybrid vehicle systems use electrical energy for many purposes including infotainment, lighting, battery management, various safety sensors (TPMS, ADAS, etc.), and wireless communication. With each new system added to a vehicle, these systems will continue to load the central power source of the vehicle.

D. High Level of Dependence on Vehicle Batteries or Alternators

ICE vehicles have placed a higher demand on alternators to generate enough electricity to keep up with the demand.

Additionally, as electric vehicles see higher levels of demand for electrical power, their range will further diminish due to increased usage of their battery-powered systems. There is a great need to reduce this dependency through the inclusion of other battery alternatives.

E. Need for Sustainable, Passive Energy Solutions

As the world moves toward green tech, the demand for innovative sorts of energy-efficient, passive-energy systems will develop into more effective and efficient methods of producing energy for vehicles. If an energy-harvesting, vibration-based system could harvest energy from vibrations in the ambient environment without disrupting ride comfort or requiring any additional fuel usage, then we will end up with much more environmentally friendly vehicles.

III. Proposed Methodology and System Architecture

A. Overall Architecture

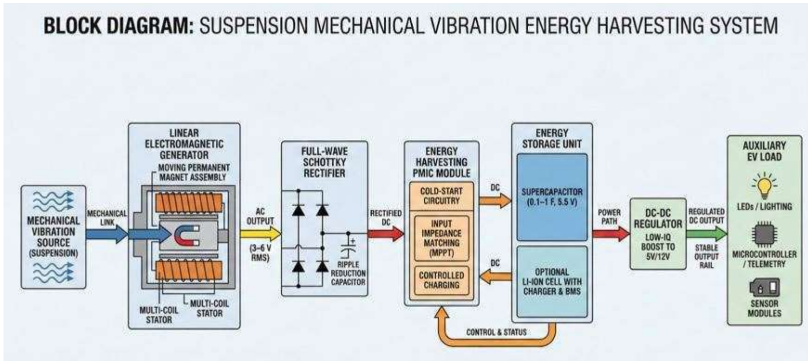

Fig. 1. Block diagram of the suspension mechanical vibration energy harvesting system.

Suspension System (Vibration Coming In)
This block is a model of the mechanical vibrations generated by the vehicle suspension in motion. Road bumps, rough surfaces, forces of braking and dynamic loads cause the oscillations of the suspension in vertical direction. These vibrations are the main source of energy for the whole harvesting system.

Linear Electromagnetic Generator (Moving N52 Magnets + Fixed Coils)
A set of strong N52 neodymium magnets is suspended from the suspension, moving relative to fixed copper coils in this block. The relative motion of magnet and coil produces a variable magnetic flux. This generates an alternating electrical voltage according to Faraday's law of electromagnetic induction.

Induced AC Voltage
Raw AC voltage is being produced by the electromagnetic generator. This voltage will have some amplitude and frequency depending on speed and amount of suspension movement. This is usable energy but it has to be conditioned before it can power electronic devices.

Bridge Rectifier Circuit (Schottky Diodes 1N5819)
This block rectifies the induced AC voltage to DC voltage using fast response Schottky diodes. The rectifier permits current to flow in one direction only, giving a smooth pulsating DC output. Schottky diodes are used because they have a very low forward voltage drop, which makes the system more efficient at low harvested voltages.

Boost Converter
Boost converter is used to step up the low level of rectified DC voltage to the higher level and more stable voltage. It compensates for the change in the strength of the vibration by adjusting the output. This takes the harvested energy to a usable level of power to be stored or used directly.

Super Cap Bank (5-10F With Balancing Resistors)
This block stores the harvested energy in high capacitance supercapacitors which can be charged/discharged rapidly. Balance resistors are used to make sure that each capacitor in the bank has an equal voltage so they do not get overcharged. The bank serves as an intermediate stage to smooth the fluctuations of harvested energy.

12V DC Output (Regulated)
The output regulation process ensures that the generated output voltage supplied to the load remains at a constant 12V. It also safeguards the load from experiencing any surge or drop in voltage due to the presence of an inconsistency in the vibration input. The resulting system can be applied in automotive electronic loads. Vehicle Loads (Sensors/Indicators/Microcontroller).
The last component denotes the load which will be powered using the extracted energy. It can comprise such components like sensors, LEDs, and microcontrollers in vehicular applications. Through vibration energy extraction, the developed system generates energy to supplement the energy supplied to the load by the battery. Vehicle Loads (Sensors/Indicators/Microcontroller).

B. Components Used

N52 Neodymium Magnets
Strong permanent magnets are employed to provide strength to the linear electromagnetic generator. The magnets comprise the moving magnetic core within which an alternating magnetic field is established when the magnetic core is reciprocated against the coils. Thus, an alternating voltage is produced in the coils. These high-density flux-producing magnets help produce higher efficiencies when harvesting energy.

Copper Coil Assemblies (36 AWG, 450 Turns Each)
The coils that make up the electromagnet component are stationary and comprised of fine-gauge copper wire. There are a total of six coils constructed to align with the stack of electric magnetic coils so that maximum flux is produced. The number of turns on the coils and their wire diameter have been optimized to produce a large amount of induced EMF, while having a small profile.

Schottky Diodes (1N5819 / SS14)
Utilizing Schottky diodes in the full-wave bridge rectifier allows for minimal energy loss through converting from an AC signal to a DC signal.

Filter Smoothing Capacitor ($\mathbf{1000}\,\mu\boldsymbol{F}$, 16 Volts)
A large capacitance electrolytic filter capacitor smoothes the dc output from the bridge rectifier. This will reduce the voltage ripple produced at the output of the bridge rectifier, allowing for stabilization of power for downstream circuits.

Supercapacitors (5 to 10 Farads at a minimum of 5.5 Volts)
With Balancing Resistors, the energy harvested by the linear electromagnetic generator is stored within two super capacitors having high capacitances. Two balancing resistors across the two capacitors ensure voltage equalization, and therefore the capacitors are protected from having unequal voltage being placed upon them due to the series configuration. Super capacitors can be rapidly charged and discharged, which makes them suitable for low-power harvesting applications.

DC to DC Boost Converter (XL6009/MT3608)
This is a boost converter that will regulate the variable DC storage voltage to maintain a stable output voltage of 12 V providing continuous power to the load, even if the load vibrates at different intensities.

Microcontrollers (ATtiny85, Arduino Nano)
Microcontrollers will monitor, process, and display the harvested energy; the Arduino Nano will perform the I/O operations and display, while the ATtiny85 is used in a small low-power circuit. Both require a regulated 5V logic power supply from the regulated system.

MOSFET (IRLZ44N)
A logic-level N-Channel MOSFET, to switch and protect the loads. It can effectively carry high current and protect against backflow or damage to inductive devices.

Free-Wheeling Diode (1N5819)
A free-wheeling diode placed across inductive devices (coils or switching devices) to prevent voltage spikes. Protects the MOSFET and other sensitive electronic devices.

Other Passive Components
The following are passive components that will provide local decoupling: 47 uF Electrolytic Capacitors for local decoupling, (100ohm, 10k, 1k, 2.2k, etc.) Resistors for sensing, biasing and balancing, 100k Trimpots for adjusting thresholds. Boost inductors, input/output capacitors for stability of the converter circuit etc. These passive components support signal conditioning, filtering, regulation and protection of circuit components.

C. Working Procedure

In this case, 8.1 V peak AC is estimated to be generated from the vibration of the vehicle suspension at a frequency of about 10 Hz.The Ambient Vibration Energy Harvesting System functions based on the transformation of the vertical movement of the suspension of a vehicle into electrical energy via electromagnetic induction.
Vehicles have vibrations in their suspension systems because of factors such as road unevenness, accelerations, and variations in loads applied. These vibrations have a lot of mechanical energy, but they are wasted in form of heat in conventional dampers. The device makes use of these vibrations without interfering with its main

function. The vibrations in the suspension induce motion in the moving magnet system, which oscillates in a 3D-printed cylindrical tube. The permanent magnet system has high strength N52 neodymium magnets arranged in pairs to provide a stable magnetic field. The repulsion magnets placed at the ends make the motion steady, thus ensuring consistent

Six static copper coils surround this magnet tube, each containing about 450 turns of 36-AWG enameled copper wire. As the magnet passes through the coils, there will be dynamic changes in magnetic flux through the coil alternating voltage (AC) in each of the coils. Given that the coils are arranged in series, the resulting output voltage from their combination is expected to have approximately 8.1 volts AC RMS (≈11.45 volts peak).

As we cannot use the AC output from the coils for charging electronic devices, the output is passed on to a full wave bridge rectifier composed of 1N5819 Schottky diodes. The advantage of using Schottky diodes in this application is that these components have very low forward voltage drop, thus increasing efficiency in converting voltages especially when working with small amounts of harvested energy. This circuit changes the alternating current to pulsating direct current. A 1000 µF smoothing capacitor is utilized

The resultant energy is stored in a battery of two supercapacitors with capacitance of 5-10 F each, coupled in series with balancing resistors. Supercapacitors are the best choices for vibration energy harvesting devices owing to their extended cycle life, rapid charge rate, and high-power density. They will serve as a storage device that accumulates energy on the basis of the presence of vibrations and outputs a steady current to the subsequent component.

For the purpose of providing a constant output, the accumulated voltage goes through a DC-DC boost converter like XL6009 and MT3608 which raises the output voltage level to 12 V DC. Thus, it will guarantee constant voltage supply irrespective of fluctuations in the vibration strength. Finally, the output energy can be utilized to power small gadgets such as IoT sensors, indicators, microcontrollers (Arduino Nano, ATtiny85).

As a conclusion, the operation principle of the presented system lies in transforming vibrations into AC electricity, accumulating the latter, and regulation of the output voltage to 12 V DC. It provides an autonomous and maintenance-free process of harvesting energy in vehicles.

The setup not only generates electricity from mechanical vibrations but also makes sure that there is proper energy conditioning during the processes of rectification and boost conversion. Rectification gets rid of the alternating properties of the induced voltage and creates an appropriate source of power in the form of direct current. Boost conversion then takes place, where this current is boosted up to a useful level. The output power thus generated ensures that there is proper power delivered to the load despite the changing vibration levels. The regulated power ensures that the system has enough power to drive small consumption electronic devices, which makes the entire process independent and efficient.

The overall operation of the system reflects the conversion chain from basic mechanical vibration energy through to usable electrical energy (in a controlled voltage) in a very smooth manner. Each time a suspension moves, its moving magnet generates an AC voltage which corresponds to the level of vibration at that specific moment in time. Each of the AC signals is rectified and conditioned immediately after generation to provide the harvester with a low-loss continuous DC output voltage. This low loss DC output is possible due to the lower forward voltage drop (when compared to standard diodes) through the use of Schottky diodes. This is especially important for properly using the harvested energy because very low levels of power are possible at times. The harvested DC output voltage charge will be stored in a supercapacitor bank that will store all charges supplied to it from its convertor so that whenever vibrations occur (from motion) the supercapacitors will charge. The converted energy will be provided to the boost converter as a regulated input source so that the output voltage to the load will remain regulated, regardless of the fluctuations in the mechanical input. The boost converter will generate a regulated output voltage of 12 volts, making it compatible with all automotive electrical equipment. The entire system is a completely Passive (no maintenance required) Power Generator that operates automatically as long as the vehicle is in motion.

IV. Mathematical Modeling

The theoretical performance of the linear electromagnetic generator is governed by Faraday's Law of Induction. The magnetic flux (Φ) passing through a single coil is defined as:

$$\Phi = B \cdot A$$

where B represents the magnetic flux density and A is the cross-sectional area of the coil. The area can be calculated using $A = \pi \cdot r^2$, with r being the radius of the coil. As the suspension system oscillates at a given frequency (f), the moving magnets create a time-varying magnetic field. According to Faraday's Law, the total electromotive force (EMF) induced in a coil with N turns is:

$$V\_induced = N \cdot (d\Phi / dt)$$

The resulting alternating current (AC) output is characterized by its peak voltage (V_peak) and its root-mean-square voltage (V_RMS), which are related by the standard equation

$$V\_RMS = V\_peak / \sqrt{2}.$$

To convert this AC signal into usable direct current (DC), a full-wave bridge rectifier using Schottky diodes is employed. The final rectified DC voltage ($V\_rectified$) is derived from the peak voltage while accounting for the forward voltage drops inherent to the diodes. Finally, the total electrical power output (P) delivered by the harvester is the product of the output voltage (V) and the output current (I):

$$P = V \cdot I$$

V. Experimental Setup

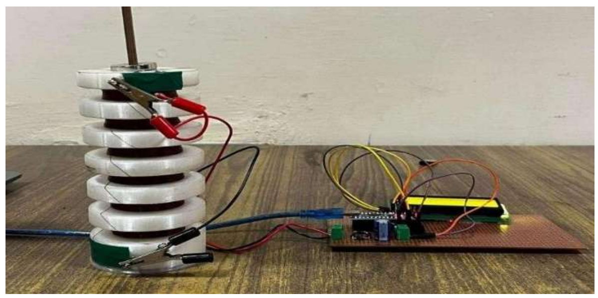

Fig. 1. Experimental Setup for Vibration Energy Harvesting.

The prototype of the vibration energy harvesting system shown in Figure contains a suspension mechanism and an electric generator that converts linear vertical movement into a power output from the mechanical energy being harvested during vibrations. This is the basic idea behind how this type of system uses mechanical vibration energy and turns it into electrical energy.

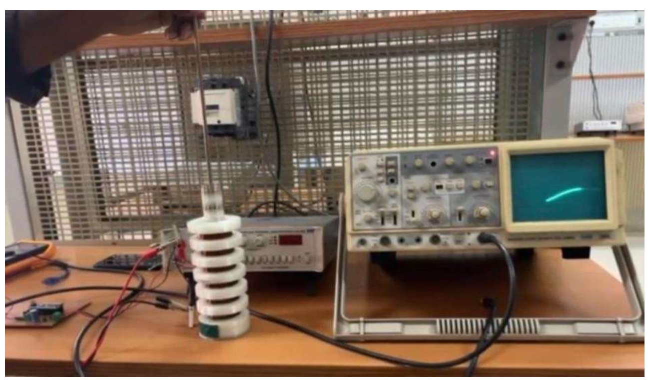

Fig. 2. Experimental Measurement Setup with Oscilloscope and Suspension Harvester

Figure shows the measurement equipment used to evaluate the output of the vibration energy harvesting prototype. The oscilloscope is connected to the suspension-mounted generator and is used to view the voltage waveform as it is created during mechanical shock. This test equipment enables the measurement of performance of the energy harvesting system to be conducted accurately under realistic testing conditions.

VI. Result and Discussion

The experimental evaluation of the vibration energy harvesting prototype yielded promising results across a typical electric vehicle suspension operating frequency range of 5 to 20 Hz. Measurements indicated that the induced AC voltage per individual coil was approximately 1.909 V (peak AC). By connecting the six coils in series, the generator achieved a total combined AC voltage of approximately 8.1 V (peak AC). Following the rectification stage using the Schottky diode bridge, the system produced a DC output of roughly 9.68 V. The harvester was able to deliver an output current of 97 mA per suspension, resulting in a usable power output of 1.16 W per unit. When extrapolated to a standard vehicle configuration utilizing four independent suspension units, the estimated total power generation reached approximately 4.64 W. Finally, the integrated DC-DC boost converter successfully regulated this harvested energy to a stable 12 V DC output. These performance metrics demonstrate that the system is fully capable of providing sustainable power to low-power auxiliary electronics, such as LED indicators, microcontrollers, and IoT sensor modules.

VII. Conclusion

This study provides evidence of a previously unproven method for taking advantage of the naturally occurring ambient vibration present in vehicle suspension systems to collect and convert ambient vibration energy into usable electrical energy using a spring-based generator. The research was performed using data collected from both asynchronous and timestamped data relating to vibration (mechanics) events. This allowed the authors to show how real-time monitoring and measurement of the behavior of the mechanical vibrations that occur in vehicle suspension systems can be achieved and accurately performed on a real-time basis. The experiments performed verified that the motions generated through the use of a vehicle's suspension system would be able to generate an electrical output, thus supporting the potential for using vibration-based energy harvesting technology. Systematic observation and signal processing has allowed the prototype to provide evidence regarding both the irregularity of the vibrational inputs and their relationship to energy produced from vibrational inputs.

Furthermore, the findings from this work support the ability of vibration-based energy harvesting devices to operate without requiring the existence of a synchronous or continual event pattern in order to generate energy. Finally, by using real-time monitoring methods, the ability of the energy harvesting devices to perform under different mechanical environments can be quantitatively measured. The findings suggest energy harvesters could be integrated into vehicle suspension systems for use to power electrical devices and electronic sensors. Although the prototype used for this project was not complex, it demonstrated the basic concept behind how this type of technology works and therefore creates new opportunities for developing better performing systems with subsequent design optimizations of the materials, damping and electrical components that would enable higher energy production and prolong the life of the energy harvesting systems.

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