

TURBOCOMPRESSOR ELÁSTICO: CONCEITO TEÓRICO PARA RECUPERAÇÃO DA ENERGIA POTENCIAL ELÁSTICA DA SUSPENSÃO AUTOMOTIVA PARA ASSISTIR À OPERAÇÃO DE E TURBO

ELASTIC TURBOCHARGER: THEORETICAL CONCEPT FOR RECOVERING AUTOMOTIVE SUSPENSION ELASTIC POTENTIAL ENERGY TO ASSIST ETURBO OPERATION

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Resumo

Introdução: Sistemas convencionais de recuperação de energia em veículos geralmente se concentram na frenagem regenerativa ou no aproveitamento dos gases de escape, negligenciando outras fontes potenciais. A energia elástica armazenada temporariamente pelas molas de suspensão durante a condução é comumente dissipada por amortecedores. **Objetivo:** Este estudo propõe e analisa teoricamente o conceito do Turbocompressor Elástico, um sistema de recuperação de energia baseado na compressão das molas de suspensão, com o objetivo de alimentar um turbocompressor elétrico (eTurbo). **Metodologia:** A abordagem teórica fundamenta-se na aplicação da Lei de Hooke e dos princípios da conservação de energia. Foram adotados parâmetros físicos arbitrários, porém coerentes, para estimar a energia potencial elástica gerada a cada evento de compressão e convertê-la em potência elétrica via um motor síncrono de ímã permanente (PMSM). **Resultados:** Os cálculos indicam que uma única compressão de mola pode fornecer até 22,5 J de energia útil, correspondendo a uma potência instantânea de 225 W e torque de 2,5 N·m a uma velocidade angular de 150 rad/s. **Conclusão:** O sistema demonstrou viabilidade teórica e potencial aplicação em veículos híbridos ou de alto desempenho, desde que adequadamente integrado à suspensão traseira e acoplado a um sistema eficiente de conversão mecânico-elétrico.

Palavras-chave: Molas de suspensão; Energia potencial elástica; Sistema de recuperação de energia; Máquina síncrona de ímã permanente; Turbocompressor elétrico.

Abstract

Introduction: Conventional vehicle energy recovery systems typically focus on regenerative braking or exhaust gas utilisation, neglecting other potential sources. The elastic energy temporarily stored in suspension springs during vehicle motion is usually dissipated by dampers. **Objective:** This study proposes and theoretically analyses the concept of the Elastic Turbo, an energy recovery system based on suspension spring compression, aiming to power an electric turbocharger (eTurbo). **Methodology:** The theoretical framework is based on Hooke's Law and the principle of energy conservation. Arbitrary yet physically consistent parameters are adopted to estimate the elastic potential energy generated per spring compression and its conversion into electrical power using a permanent magnet synchronous motor (PMSM). **Results:** Calculations indicate that a single compression event can provide up to 22.5 J of recoverable energy, equivalent to an instantaneous power output of 225 W and a torque of 2.5 N·m at an angular velocity of 150 rad/s. **Conclusion:** The system demonstrates theoretical feasibility and potential applicability in hybrid or high-performance vehicles, provided it is properly integrated into the rear suspension and coupled with an efficient mechanical-to-electrical conversion interface.

Keywords: Suspension springs; Elastic potential energy; Energy recovery system; Permanent magnet synchronous motor; Electric turbocharger.

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1. Introduction

With the growing demand for sustainable and efficient solutions in the automotive industry, energy recovery systems have become essential for improving performance and reducing waste. The most common approaches, such as regenerative braking and exhaust gas-driven turbochargers, are already widely implemented in hybrid and high-performance vehicles, while several other systems are being studied and developed to recover various form of

waste energy, including mechanical vibrations and suspension dynamics^{1,2,3}.

However, a significant amount of mechanical energy resulting from suspension oscillations is still dissipated as heat through dampers, remaining underutilised⁵. Among the various energy recovery strategies, suspension-based systems remain less explored when compared to kinetic or thermal energy recovery solutions^{1,2,6,9}.

This paper introduces the concept of the

Elastic Turbocharger, a theoretical energy recovery system based on the compression of vehicle suspension springs. The proposal aims to capture the elastic potential energy stored during vertical suspension movements and convert it into electrical energy through a mechanical-to-electrical conversion system coupled to a permanent magnet synchronous motor (PMSM)¹⁰. The recovered energy is directed exclusively to power an electric turbocharger (eTurbo), enabling rapid activation without relying on exhaust gas pressure—a common limitation in conventional turbocharging systems^{6,8}.

By targeting a source of energy typically wasted, the Elastic Turbocharger offers a supplementary energy recovery pathway with potential applications in hybrid or performance-oriented vehicles. Additionally, this approach aligns with global efforts towards more sustainable transportation by improving overall energy efficiency without increasing fuel consumption or emissions^{3,7,11}.

This study develops a theoretical model based on classical mechanics and energy conversion principles to estimate the recoverable energy and assess the viability of the system under ideal conditions. It aims to contribute to the expanding body of research in vehicle energy harvesting, complementing existing technologies such as regenerative braking, waste heat recovery, and kinetic energy recovery systems^{1,4,5,9}.

2. Methodology

2.1 Theoretical basis and approach

The Elastic Turbocharger is a conceptual

energy recovery system based on the transformation of elastic potential energy—naturally generated by suspension springs during vehicle motion—into electrical energy. Unlike traditional systems that rely on braking or exhaust gases, this proposal captures suspension oscillations using a mechanical interface to transfer motion to a generator. Similar approaches in energy recovery, though commonly focused on exhaust systems, kinetic recovery, or flywheel storage, have demonstrated significant potential to enhance fuel efficiency and sustainability in both conventional and hybrid vehicles^{1,2,3}.

Hooke's Law governs the spring's elastic force (Eq. 1):

$$F = kx \quad (1)$$

where F is the restoring force (N), k is the spring stiffness constant (N/m), and x is the spring displacement from its equilibrium position (m)⁴.

The elastic potential energy, E_e , is derived from this law and expressed as Eq. 2:

$$E_e = \frac{1}{2} kx^2 \quad (2)$$

This relation forms the basis for calculating the energy stored during a compression event. The relevance of this mechanical formulation is reinforced by multiple studies that analyse energy harvesting technologies in vehicles, highlighting suspension systems as an emerging but underexplored domain for energy recovery^{2,3,5}.

2.2 Energy recovery and conversion efficiency

To estimate the effective energy recovered, E_r , it is necessary to account for system losses. A global mechanical-electrical efficiency factor, η , is introduced:

$$E_r = \eta \cdot E_e \quad (3)$$

This equation provides the net electrical energy available after conversion, considering frictional, mechanical, and electromagnetic losses. Similar considerations regarding energy conversion efficiency are discussed in the context of exhaust energy recovery systems, thermoelectric generators, and flywheel storage technologies^{1,6,7}.

2.3 Instantaneous power and torque output

Assuming a suspension compression occurs within a short time interval, ΔT , the instantaneous power, P_i , delivered to the generator is estimated by:

$$P_i = \frac{E_r}{\Delta T} \quad (4)$$

In addition to this transient approach, the electrical power output can also be calculated via torque and angular velocity using the general power relation:

$$P_e = \eta \cdot T \cdot \omega \quad (5)$$

where P_e is the electrical power output (W), T is the torque applied to the generator shaft ($N \cdot m$), and ω is the angular velocity (rad/s). This formulation is consistent with models applied in other energy recovery systems technologies, including flywheels, kinetic recovery systems, and exhaust-based energy recovery mechanisms^{1,8,9}.

Those equations enable the theoretical evaluation of energy and power values under idealised conditions, using physically consistent but arbitrarily selected parameters.

2.4 Theoretical integration and implementation framework

The successful implementation of the proposed energy recovery system depends not only on its theoretical feasibility, but also on its mechanical and electrical integration into the vehicle's existing architecture. While the mathematical foundations presented earlier describe the physical mechanisms for energy capture and conversion, practical considerations must guide the system's actual design.

The interface between the suspension spring and the generator must accommodate short-stroke, high-frequency displacements without introducing excessive friction or altering suspension behaviour. Comparable mechanical challenges are widely discussed in the literature on exhaust energy recovery and kinetic recovery systems, where factors similar to thermal constraints, mechanical backlash, and packaging limitations directly impact efficiency^{1,3,6}.

From an electrical perspective, although the system operates independently of the vehicle's hybrid drivetrain, integration with the onboard power electronics and energy management unit (EMU) is essential. Synchronisation between energy capture events and eTurbo activation requires a basic control interface to coordinate power flow, prevent overlap with regenerative braking systems, and avoid electrical overloads. These control challenges are

like those faced in managing multiple energy recovery paths in modern hybrid vehicles^{2,7}.

Furthermore, a modular system architecture could allow the Elastic Turbocharger to be adapted to different platforms with minimal modifications. By designing it as a plug-in module aligned with existing suspension geometries, the system could be integrated as an auxiliary energy path without extensive redesign of the vehicle's structure or control strategy^{3,11}.

3. Results

To verify the theoretical feasibility of the proposed energy recovery system, a simplified analytical model was implemented using physically consistent yet arbitrary parameters. The objective was to quantify the recoverable energy and resulting electrical output during a typical suspension compression event. Similar theoretical approaches have been validated in previous studies on suspension-based energy harvesting systems¹⁻⁵.

3.1 Elastic energy storage

The amount of energy stored in the suspension spring during compression was calculated using Equation (2). Considering a spring constant of $k = 30 \text{ kN/m}$, which reflects typical values for high-performance vehicle suspensions⁵, and a maximum displacement of $x = 0.05 \text{ m}$, the stored energy is:

$$E_e = \frac{1}{2} \cdot 30000 \cdot 0.05^2 \therefore E_e = 37.5 \text{ J}$$

This represents the total energy available from a single spring compression. In

dynamic driving conditions, where frequent suspension movements occur, the cumulative energy recovery can become significant, a principle also highlighted in other energy harvesting systems applied to automotive applications^{1,3}.

3.2 Recoverable electrical energy

Assuming a global mechanical-to-electrical conversion efficiency of $\eta = 0.60$, the effective recoverable electrical energy per event, using Equation (3), is:

$$E_r = 0.60 \cdot 37.5 \therefore E_r = 22.5 \text{ J}$$

This is the net energy available to be used by auxiliary systems, such as the eTurbo, per oscillation. Although relatively modest on its own, the cumulative effect across multiple events could offer a feasible energy source. Similar energy magnitudes are also noted in regenerative systems based on exhaust gas recovery and kinetic energy recovery^{6,8,9}.

3.3 Instantaneous power output

If the compression occurs over a short interval of $\Delta T = 0.1 \text{ s}$, the instantaneous power delivered to the generator is calculated using Equation (4):

$$P_i = \frac{22.5}{0.1} \therefore P_i = 225 \text{ W}$$

Even though the system operates in short pulses, the recurrence of spring oscillations during vehicle motion—especially on irregular tracks—may result in a meaningful energy supply. This pulse-based nature is similar to that observed in flywheel storage systems during rapid energy transfers⁷.

3.4 Output torque

Finally, the torque transmitted to the PMSM is calculated using Equation (5), assuming an angular velocity of $\omega = 150 \text{ rad/s}$.

$$225 = 0.60 \cdot T \cdot 150 \therefore T = \frac{225}{0.60 \cdot 150} \therefore T = 2.5 \text{ N} \cdot \text{m}$$

This confirms that the system can produce torque suitable for driving an electric turbocharger under dynamic conditions, comparable to the torque levels observed in small-scale electric machines applied in hybrid energy recovery systems¹⁰.

3.5 Parametric variation of spring stiffness

To evaluate the influence of spring stiffness on energy storage, Equation (2) was applied using a constant displacement of 0.05 m and varying spring constants. For a spring constant of 20 kN/m , the stored energy is 25 J ; with 30 kN/m , the value reaches 37.5 J ; and with 40 kN/m , the result is 50 J . These values demonstrate a directly proportional relationship between stiffness and recoverable energy, which is consistent with findings from previous suspension energy recovery studies⁵.

As the spring constant increases, the energy stored per compression event

also increases linearly. This suggests that vehicle setups with stiffer suspensions may offer greater energy recovery potential, provided that the displacement remains sufficient.

3.6 Influence of displacement amplitude on recoverable energy

The energy stored in the suspension spring is highly sensitive to the displacement amplitude due to its quadratic relationship, as described by Equation (2). For instance, with a spring constant of 30 kN/m , a compression of 0.03 m yields 13.5 J , while 0.05 m results in 37.5 J . When the displacement increases to 0.07 m , the stored energy rises sharply to 73.5 J .

This non-linear growth highlights the importance of oscillation amplitude in determining the energy recovery potential. In dynamic conditions with higher suspension travel—such as on uneven tracks or during aggressive driving—significantly more energy may be harvested per cycle. This behaviour aligns with models in other energy recovery systems, including waste heat recovery and kinetic energy recovery, where energy scales disproportionately with input amplitude^{6,8,9,11}.

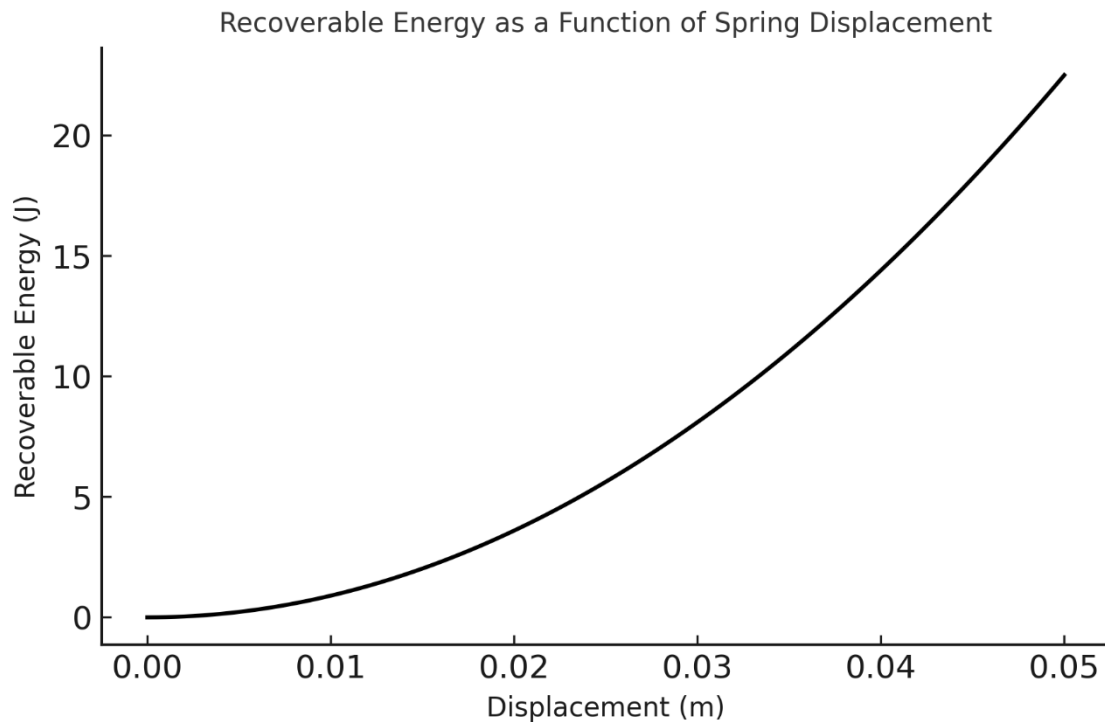


Figure 1 – Relationship between recoverable energy (E_r) and suspension displacement amplitude (x). The graph shows the quadratic increase in E_r as the spring displacement grows from **0.01 m** to **0.07 m**, assuming a spring constant of **30 kN/m**. This trend highlights how small increases in suspension travel lead to significantly greater recoverable energy, reinforcing the sensitivity of the system to oscillation amplitude.

4. Discussions

The results obtained from the theoretical model demonstrate the physical plausibility of recovering elastic energy from suspension systems and redirecting it to support an auxiliary subsystem, such as an electric turbocharger. Although the recovered energy per oscillation event is modest in absolute terms, its magnitude—**22.5 J** per cycle and **225 W** of instantaneous power—is significant when considering the short duration of the compression and the frequency with which such events occur in real driving scenarios.

The torque value of **2.5 N · m**, obtained under a reasonable angular velocity, further supports the potential application of this energy in driving a compact electric machine. This is particularly relevant for eTurbo systems, which require rapid response in short bursts rather than sustained continuous operation. The pulse-like nature of suspension oscillations aligns naturally with the operational profile of electrically assisted compressors, which have been increasingly adopted in modern energy recovery architectures^{6,8}.

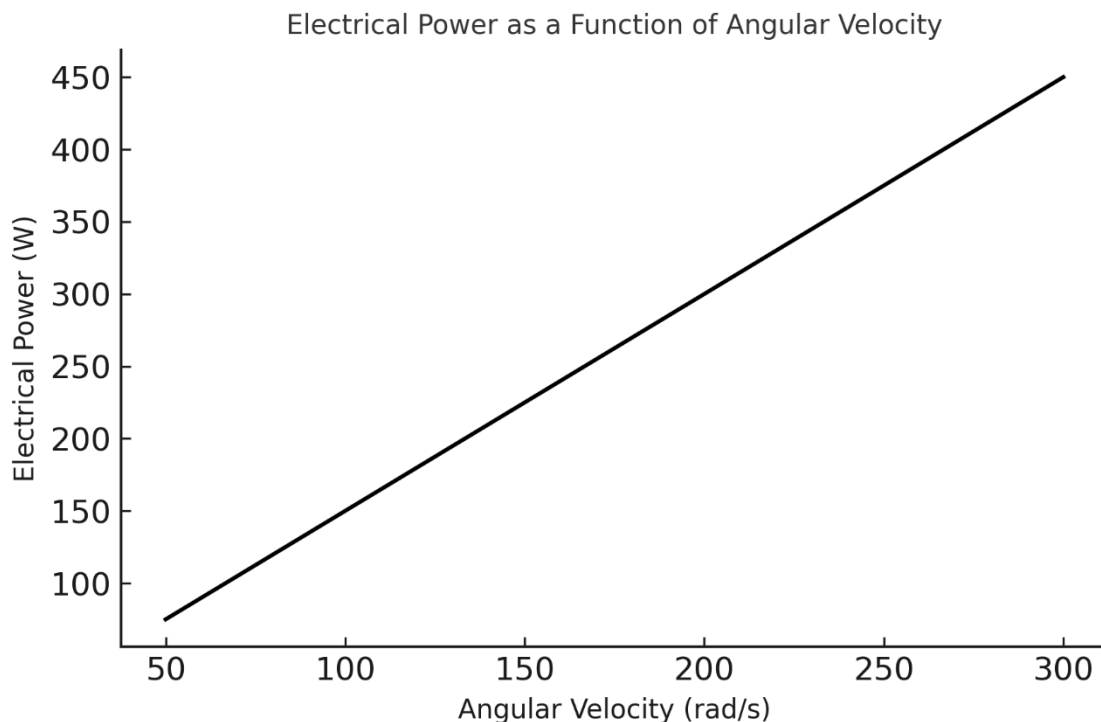


Figure 2 – Relationship between electrical power output (P_e) and generator shaft angular velocity (ω). The graph demonstrates how the power output increases proportionally with ω , considering a constant torque of $2.5 \text{ N} \cdot \text{m}$ and an overall efficiency of 0.60 . This reinforces the dependency of power generation on the generator's rotational speed, especially under transient suspension oscillations.

Parametric analyses revealed that the energy stored increases linearly with the spring stiffness, indicating that vehicles equipped with firmer suspensions—such as sports or utility vehicles—may yield greater energy recovery, provided sufficient compression occurs⁵. Moreover, the elastic energy grows quadratically with displacement amplitude, meaning that even small increases in suspension travel result in disproportionately higher recoverable energy⁴. This sensitivity highlights the system's potential to perform more effectively under dynamic driving conditions or on uneven road surfaces, where larger suspension oscillations are expected.

These characteristics are comparable to other mechanical energy recovery systems explored in the literature, such as kinetic energy recovery systems (KERS) and flywheel-based mechanisms, which also rely heavily on transient energy capture and high efficiency in mechanical-to-electrical conversion^{7,9}. Additionally, studies on retrofitting energy recovery systems into internal combustion engine vehicles indicate that suspension-based recovery could be a valuable complementary solution to existing systems similar to regenerative braking or exhaust gas recovery^{1,2,3}.

Nonetheless, it is important to acknowledge that the present analysis is

based on idealised assumptions, including perfect energy transfer, absence of frictional losses in mechanical linkages, and instantaneous conversion. In real-world implementations, factors such as damping characteristics, packaging constraints, actuator response time, and integration with vehicle dynamics systems would significantly affect the overall performance⁵.

Moreover, the scalability of the concept depends on the efficiency of the conversion mechanism and its ability to operate under the wide range of frequencies and displacements observed in suspension behaviour. These elements would require further investigation through dynamic simulations and experimental validation to ensure operational reliability and energy gains under diverse road and load conditions^{3,5}.

Even so, the simplified model serves as a theoretical proof of concept, revealing a promising direction for alternative energy recovery strategies in automotive systems. By exploring a previously underutilised energy source—suspension oscillations—the Elastic Turbocharger introduces a novel way to enhance performance, particularly in hybrid or performance-focused vehicles where energy efficiency and responsiveness are critical¹¹.

5. Conclusion

This study presented a theoretical investigation of the Elastic Turbocharger concept, an energy recovery system designed to convert the elastic potential energy generated during suspension spring compression into usable electrical power. By applying classical mechanical principles and physically consistent

parameters, it was demonstrated that a meaningful amount of energy can be recovered from each oscillation event, sufficient to support auxiliary systems such as an electric turbocharger (eTurbo).

The simplified model yielded promising numerical results: **22.5 J** of recoverable energy and **225 W** of instantaneous power per compression event, along with **2.5 N · m** of torque at **150 rad/s**. In addition, the parametric analysis showed that energy recovery scales linearly with spring stiffness and quadratically with displacement amplitude. This highlights the importance of both suspension design and dynamic operating conditions in determining the system's performance.

Although the model operates under idealised assumptions, with no energy losses or integration constraints, it successfully demonstrates the conceptual viability of harvesting suspension dynamics for functional energy recovery. The pulse-like nature of the system aligns naturally with the operational demands of eTurbos, which benefit from short bursts of high-power input rather than continuous delivery.

Future work should include simulations and experimental validation to account for mechanical losses, packaging feasibility, and control integration. Investigating the impact of road profiles, suspension geometries, and vehicle categories may also help refine the system's applicability and design optimisation.

Therefore, the Elastic Turbocharger introduces an innovative and theoretically sound approach to alternative energy recovery in vehicles. It

opens a promising path for supplementary electrification strategies, particularly in performance or hybrid platforms where responsiveness, compactness, and energy efficiency are essential.

6. Conflict of interest

The author has no conflict of interest.

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This article represents the first step in what the author envisions as a long-term contribution to the field of energy-

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