

Development of a Spring-Based Automotive Starter

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ABSTRACT

Automotive starting systems require substantial amounts of mechanical energy in a short period of time. Lead-acid batteries have historically provided that energy through a starter motor. Springs have been identified as an alternative energy storage medium and are well suited to engine-starting applications due to their ability to rapidly deliver substantial mechanical power and their long service life. This paper presents the development of a conceptual, spring-based starter. The focus of the study was to determine whether a spring of acceptable size could provide the required torque and rotational speed to start an automotive engine. Engine testing was performed on a representative 600 cc, inline 4-cylinder internal combustion engine to determine the required torque and engine speed during the starting cycle. An optimization was performed to identify an appropriate spring design, minimizing its size. Results predict that the test engine could be started by a torsional steel spring with a diameter and length of approximately 150 mm, similar in size, but lower weight than an electrical starting system of the engine. A proof-of-concept prototype has been constructed and evaluated.

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1. INTRODUCTION

An increasing concern for sustainability has lead to dramatic growth of electric and hybrid-vehicles. Still, the internal combustion (IC) engine is the dominant propulsion device for automotive and commercial vehicles [1]. An increased focus on improving the fuel efficiency in these traditional vehicles fostered recent developments including the use of alternative fuels [2], reduced friction within engines [3] and efficient continuously variable transmissions [4]. Turning the engine off during idle stops will increase fuel efficiency and is widely employed in hybrids.

An IC engine is not a self-starting device as the pistons must be moving to draw in the fuel-air mixture into a cylinder and be compressed prior to combustion [5]. Thus, starting requires initial engine cranking by an auxiliary source. The minimum rotational speed required to start a typical IC engine is approximately 100 to 200 rpm [6]. However, the crankshaft torque depends on the engine type, swept volume and number of cylinders. The earliest automobile engines were started with hand cranks, where the driver was capable of providing the necessary speed and torque. This proved to be difficult and dangerous for the operator, as the engine could backfire and cause injury to the hand crank operator [7]. To address this issue, Charles Kettering patented the electric self-starter in 1915 [8]. The fundamental concept has changed little to this

day and is comprised of a battery-driven DC motor, pinion engaging transmission and a device that disengages the starter from the drive shaft once the engine is started. Since the speed of a DC motor is significantly higher than the engine requirements, the starter transmission (starter pinion and engine ring gear) has a suitable step-down ratio (approximately 1:10 to 1:20).

A starter battery stores chemical energy, which must rapidly be converted into electrical energy and supply a high current in order to start the engine. Having an energy density of approximately 140 kJ/kg [9], lead-acid storage batteries are most often used. However, the large size of the battery and large diameter copper cables are directly attributed to the need for rapid extraction of energy required by the starter. That is, the moderate power density of batteries is a fundamental design challenge. To that end, idle-stop systems are less frequently used with IC engines than hybrids, as they require an upgraded starter/generator and battery [10]. Additionally, a control system is used to monitor auxiliary loads and depth of battery discharge as protection from advanced aging. An additional drawback of large batteries is the environmental concerns that exist with manufacture and disposal of batteries [11].

Elastic energy storage has been used for hundreds of years for applications such as bows, tweezers and clocks. At approximately 0.3 kJ/kg [12], the specific energy density of a steel spring is much less than batteries and not commonly considered as a viable option for wide-spread, high energy storage. Yet despite having a low energy density, springs are able to rapidly release their stored energy. This large power density can make a spring attractive for engine starting applications. The storage attractiveness is improved when using hyperelastic springs, such as rubber with an energy density of 12 kJ/kg [12], but can raise durability concerns. Current research involves constructing springs from carbon nano-tubes (CNT), having an energy density of 800 kJ/kg and vastly exceeding the capacity of batteries [13]. Commercialization of CNT technology greatly enhances the attractiveness of a spring starting system.

Spring starters have been commercially available on small lawn mowers [14], and large remote power generators [15]. When compared to a large battery and high amperage starter motor, it is anticipated that a spring starter could have lower weight, longer life and no disposal concerns. In order to evaluate the feasibility of using an elastic storage member for the engine-starting system, this paper presents a study that determines the size of a steel torsional spring to start an four-cylinder, IC engine. The remainder of the paper is organized as follows. Section 2 introduces the conceptual model of a spring starter. Section 3 describes the representative test engine. Section 4 presents experiments used to characterize the starter motor and engine. Section 5 describes an optimization performed to select an appropriate spring. Section 6 presents the proof-of-concept prototype and evaluation.

2. DESCRIPTION OF CONCEPT

The device being evaluated is not intended to eliminate the battery. Besides starting the engine, the battery in an automobile is required for various ancillary devices. Instead, the spring starter system is expected to significantly reduce the size of the battery and associated cables.

A conceptual schematic of a spring-based mechanical starter is shown in Fig. 1. The primary feature of the system is the use of a spring rather than a battery to store energy. The spring can take many geometric forms. A spring formed through tensile bands most efficiently utilizes the material as the entire section is stressed at the same level. Springs that are formed through torsional or bending elements can use space more effectively and reduce hazard due to a potential failure [16]. Extension and torsional coil springs are widely used in general machine applications and have predictable behavior and reliability [17].

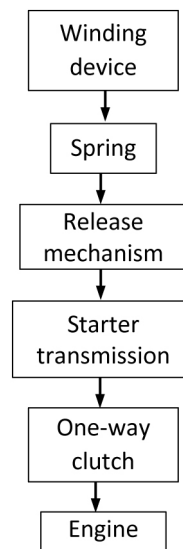


Figure 1. Conceptual model of a spring starter.

A sketch of the physical realization of the spring-based starter concept is shown in Fig. 2. One end of the spring is deflected by a worm gear drive, storing and locking energy in the spring. The other end of the spring is coupled to the engine shaft via transmission gears. A latching mechanism is placed between the spring and the transmission gears and is engaged when necessary to prevent the system from releasing energy. A one-way or overrunning clutch is mounted to the final gear of the transmission, such that the system is coupled to the engine during the starting cycle and decoupled during normal engine operation.

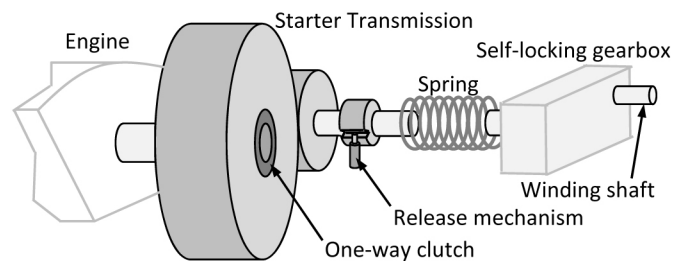


Figure 2. Physical realization of a spring starter concept.

The device is charged by rotating the input shaft to the worm gear drive while the latching mechanism is engaged. This wind can occur manually or from a novel device that is coupled to the running engine. Due to the large gear reduction within the worm gear, the spring can also be deformed by a small DC motor, powered by the alternator or small battery, which charges the spring over a longer period of time. Further evaluation of these options is left for future work.

The stored energy is discharged by releasing the latching mechanism, thus allowing the spring to exert torque on the transmission gears and transferring power to the engine. The transmission ratio can be chosen to provide a match of the torque and speed delivered by an optimal spring and the engine starting requirements.

Note that the concept described uses all the spring energy for a single crank cycle. A drawback is the inability to re-crank in the case of misfire. In this case, the driver must wait for the small dc motor to energize spring or the spring must be deformed manually (taking advantage of the large ratio in the self-locking gearbox). Further investigation into solutions for this drawback is also left for future work.

3. TEST PLATFORM

To evaluate the capability of a spring-starter system in a representative automotive application, a suitable test platform was obtained. A 1995 Yamaha XJ600S motorcycle engine was selected to serve as a platform for system development. A motorcycle was identified as having several desirable features, namely: it is easy to transport, relatively small, and has an accessible engine. The XJ600S is similar to the most common configuration of automobile engine, having an in-line four-cylinder, four-stroke IC engine equipped with an electric starter motor. The shared features suggest that if a well-sized spring starter system were to successfully crank the XJ600S engine, the design could be adapted to automotive engines. The specifications of the electric starting system on this engine provide a design goal for weight and size of the spring starter prototype.

The starting system of the Yamaha XJ600S is actuated by a Mitsuba SM-13 brushed DC motor, with a rated output of 0.8 kW [18]. According to these rating point specifications, the motor draws a peak current of 67 amps from a 12-volt lead-acid battery. The 151×106×87 mm. CBTX9-BS battery weighs 2.5 kg and is rated for 120 cold cranking amps and a capacity of 8 amp-hours.

Installed on the motorcycle, the starter motor transmits mechanical power to the crankshaft through a compound gear train. The shaft of the starter motor has 10 teeth cut into the end, and is in constant mesh with the starter clutch shaft via an idler gear. The starter clutch shaft is fitted with a one-way clutch, which in turn drives a chain that rotates the crankshaft. The starting clutch transmission provides a 27:1 gear ratio between the starter motor shaft and the crankshaft.

4. CHARACTERIZING THE TEST ENGINE

To develop a dynamic model of the engine and determine a set of design criteria, the torque, angular velocity, and duration of engine rotation provided by the electric starter system must be known. This information is not readily available and must be determined through experimental methods. This was accomplished in two steps: understand the relationship between torque and current in the starter motor and use that relationship to estimate the torque by measuring current. Once the torque constant of the motor is known, the current draw of the motor may be used to determine the torque developed during engine starting.

Starter Motor

A brushed DC motor exhibits a linear relationship between applied current I , start-up current I_0 and output torque T_s [19], represented by a torque constant k_t

$$T_s = k_t (I - I_0) . \quad (1)$$

An experimental method was used to characterize the starter motor by determining k_t and I_0 . A Prony brake, as shown in Fig. 3, was used to measure the relationship between the amperage and torque for the starter motor. A Prony brake is a form of dynamometer and is an established method of motor performance testing [20]. The Prony brake typically uses a slipping collar of radius r to exert a frictional force opposing the rotation of the output shaft. A weight W is placed on one end of a cord and a load sensor measures the force F through the other side of the cord. When the motor is switched on, the collar must overcome the friction between the cord and pulley by exerting a torque on the pulley. Starter motor torque may be found from the imbalance between W and F by summing moments about the shaft,

$$T_s = r (W - F) \quad (2)$$

The starter motor was removed from the motorcycle and assembled into the Prony brake. A pulley was fixed to the output shaft of the motor, with a cord drawn over the top of the pulley. A series of weights were hung from a loop at one end of the cord and the opposite end was attached to a load cell that was fixed to the ground. A shunt resistor was configured to measure high current draw with a voltmeter. The battery was fully charged for each test. A linear curve of the form in Eq. (1) was fit to the current-torque measurements as shown in Fig. 4. The regression constants are $k_t=0.0978$ N-mm/amp and $I_0=18.9$ amp.

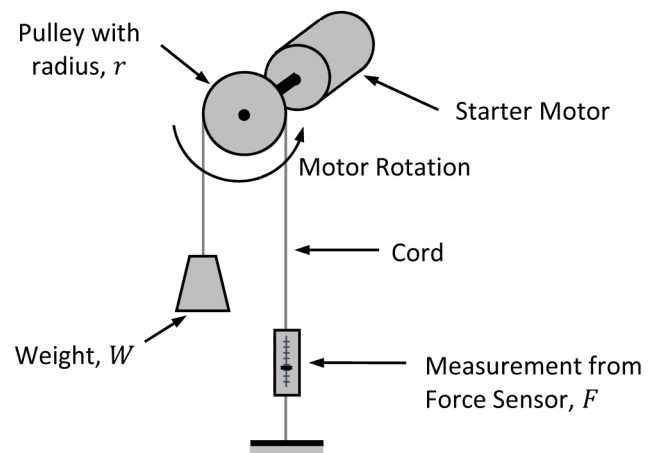


Figure 3. Prony brake test used to characterize starter motor.