Comparative performance analysis of a dual-solenoid mechanical oscillator

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Abstract. An innovative dual-solenoid electro-mechanical-vibro-impact system has been constructed and experimentally studied. Comparative studies against a mechanical spring system and a permanent magnet system have been performed, where it is shown that the dual-solenoid system is able to produce oscillations better than the permanent magnet system and more energy efficiently. Comparison with a higher-powered dual solenoid system has also been conducted where a stationary solenoid has shown to be a more dominant parameter. In addition, it is also discovered that a mechanical oscillator in the dual-solenoid system is independent of the angular frequency.

1. Introduction

Impact vibration technology was first introduced in the Soviet Union in 1940 for industrial applications. Tsaplin [1], in 1940, introduced the first impact vibration hammer for use in piling. The system consisted of a vibrating element, an eccentric mass and springs oriented in a vertical position for the piling work. Soil penetration rate by pure vibration and that produced by a vibro-impact process was compared by Tsaplin, and the rate of penetration by vibro-impact process was shown to be eight times more effective than that of a pure vibration. This phenomenon in the context of cohesion-less soil was later examined by Rodger and Littlejohn [2] in 1980 and showed the phenomenon of reduction in shear strength. The usefulness of such vibration was later demonstrated by Preobrazhenskaya [3], in 1955 and showed that the dynamic resistance of clay soil was similarly reduced as well. This impact vibration technology was later adapted in performing other earth boring works such as moling by Woo et al. [4] in 2000.

An electro-mechanical-vibro-impact system was constructed and studied experimentally by Nguyen et al. [5, 6] in 2008 and through numerical analysis by Ho et al. [7] in 2011. The system involves the use of a solenoid driven by an electrical circuit, coupled with a solid state relay, to generate large electro-magnetic forces acting on a conductor, which oscillates within the solenoid. Impacts are generated by means of a stop in the path of bar oscillations and forward progression of the device can

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then be generated, where its performance is closely related to the control frequency of the solid state relay. Lee et al. [8] in 2011 performed experimental analyses on an optimized electro-mechanical-vibro-impact system which generates impact forces using a permanent magnet as replacement to a mechanical spring, in which it is effectively acting as a highly non-linear magnetic spring. Consequently, impact forces have been generated to occur at high frequencies, which have proven to be beneficial to a downward progression rate in soil. Its magnetism is however a variable with respect to time and does not ensure longevity of the system.

This paper describes an innovative electro-mechanical-vibro-impact system with use of two solenoids at both ends of the mechanical oscillator. Three comparative studies are presented in this work to evaluate the mechanical oscillator performance of the new system. The aim of this study is to evaluate the proposed alternative to the permanent magnet system, in particular the issue on decaying magnetism in the system. Outcomes of the comparative studies will be beneficial to the future design of energy efficient and fully magnetized electro-mechanical-vibro-impact system.

2. Experimental methods and materials

Experimental approach is chosen in this study such that the responses of the mechanical oscillator can be explicitly measured and analyzed. The analysis of the system response will emphasize on oscillatory displacement made and in comparison to the system by Lee et al. [8] and Ho et al. [9]. For consistency in comparison, Ho et al.'s work is repeated in this study to serve as controlled data as well as the benchmark for comparison, denoting its maximum displacement as one. Comparison against Lee et al.'s work will be emphasized to evaluate the performance of both systems, in which both are dual-magnetized but in different configuration.

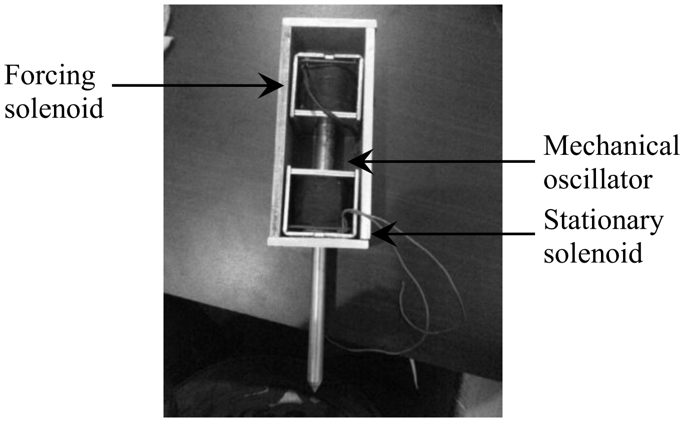

Figure 1. Proposed new dual-solenoid system.

A new electro-mechanical-vibro-impact system of dual solenoid as illustrated in Figure 1 is constructed and described. The solenoids are connected vertically with a gap of 50 mm in between and supported with aluminium plates at both vertical sides. The mechanical oscillator is placed within the two solenoids, in which the solenoid positioned on top (forcing solenoid) generates the oscillatory magnetic force and bottom (stationary solenoid) is supplied with a constant magnetic force. The new system undergoes a major change in terms of its configuration such that, previously the forcing solenoid is place at the bottom while in the new system it is installed at the top. This is due to the challenges faced by the stationary solenoid in attracting the oscillator upwards due to the gravitational pull. As such, the placement of solenoid is hence inverted so that the oscillation is made possible. The forcing solenoid is connected to power supply with 15 Volts AC and the stationary solenoid is supplied with 2.5 Volts DC. In order to eliminate the uncertainties in the design of system, similar driving circuit as [8] and [9] will be used in this study. Overall, all the environmental settings in this experiment are similar to [8] and [9] with exception on the use of an additional solenoid. For repeatability of the experiment, each data point is repeated six (6) times with uncertainty measured at 0.2 at resonance.

3. Mathematical formulations

Mathematical formulations for all three systems are derived in accordance to classical equation of motion. The motion of a mechanical spring system has been widely discuss in the literature [5-9] as expressed by (1), where m is the mass of the oscillator, F is the force from the forcing solenoid and k is the stiffness of the spring. ω is the angular frequency, x and $\ddot{x}$ is the displacement and acceleration of the oscillator, respectively and t is the time.

$$m\ddot{x} = F\sin\omega t - kx \tag{1}$$

Similarly, for a permanent magnet system, the motion of the oscillator can be expressed as,

$$m\ddot{x} = F\sin\omega t - k_{mag}x \tag{2}$$

where k_{mag} is the non-linear magnetic spring. For a dual-solenoid system, its motion is subjected to the oscillating force induced from the forcing solenoid and restoring magnetic force from the stationary solenoid. The motion of its oscillator is expressed in (3) where the negative sign shows that the placement of the solenoids is inverted as compared to the previous two and that k_{stat} is the non-linear magnetic spring induced by the stationary solenoid.

$$m\ddot{x} = -F\sin\omega t + k_{stat}x \tag{3}$$

With reference to (1)-(3), it is shown that the motion of the mechanical oscillator is dependent on two parameters. The first term on the right hand side denotes the sinusoidal force exerted from the forcing solenoid. The second term denotes the different types of restoring force as represented in the three comparative studies, a mechanical spring, a permanent magnet and a stationary solenoid. It is shown in the second term that it is a function of displacement, which is the main parameter of interest in this study. The forcing term is the controlled parameter and an independent variable throughout the study.

4. Results and discussion

Displacement of the mechanical oscillator in a dual-solenoid system is measured and compared its performance against those of [8] and [9]. Three comparative studies are presented in this paper, the first being comparison against a mechanical spring system, second, against a permanent magnet system, and finally against a higher-powered dual solenoid system. As the study is emphasizing on the innovative dual-solenoid system, the foci of discussion will revolve with the permanent magnet system and the higher-powered dual-solenoid system.

4.1. Comparison against mechanical spring system

Typically, the mechanical spring system generates a displacement of approximate 3-4 mm as reported by Ho et al in [9]. Figure 2(a) shows the displacement generated as presented by Ho et al. in [9] at angular frequency of 18 rad/s and Figure 2(b) shows the displacement generated in a repeated experiment with Ho et al.'s system under influence of different frequencies.

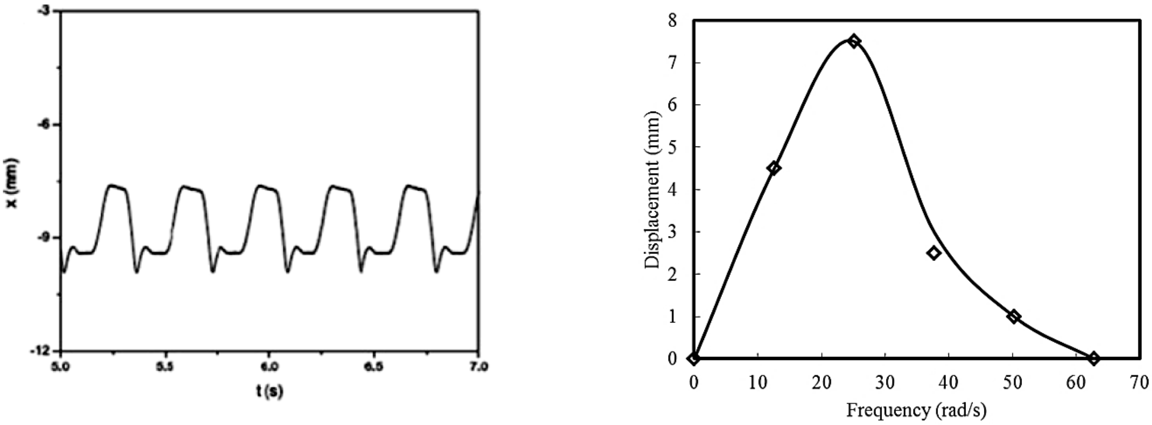

Figure 2(a). Displacement generated in a mechanical spring system at 18 rad/s by Ho et al. [9] **(b).** Displacement of mechanical oscillator under different frequencies for a mechanical spring system.

The power supplied for the mechanical spring system is rated at 15 Watts. Taking the mechanical spring system as benchmark of one, the displacement generated is compared in the dual-solenoid system. The new dual-solenoid system, on the other hand, drew only a total of 2 Watts for the forcing solenoid and 0.01 Watts for the stationary solenoid. The displacement induced for the dual-solenoid system has shown to be at 2 mm top, giving a normalized displacement of 0.38. It is, however, noted that the working range for the dual-solenoid system has shown to be rather consistent over a span of frequencies as shown in Figure 3. In addition, the power consumption is approximated a magnitude lower as compared to the mechanical spring system.

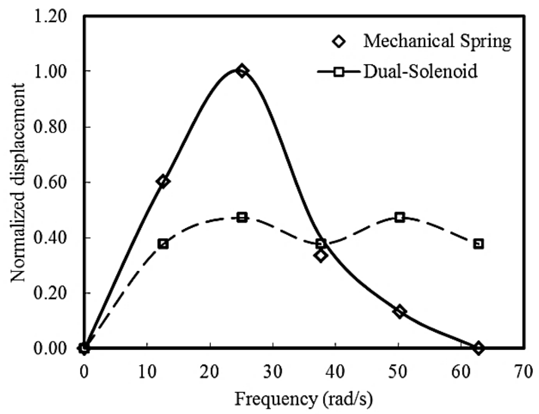

Figure 3. Comparison of mechanical spring and dual-solenoid system.

4.2. Comparison against permanent magnet system

For a permanent magnet system, the power supplied is similar to a mechanical spring system, at 15 Watts. The displacement induced by the oscillator is however smaller with only 1 mm top as presented in [8], giving a normalized displacement of 0.2 against the mechanical spring. Figure 4 shows the displacement plot of the oscillator in a permanent magnet system generated at 213.5 rad/s. It is also discovered that for a permanent magnet system, its operating window is rather narrow with angular frequency ranging from 207 to 220 rad/s, which is also shown to be one magnitude higher than the mechanical spring system.

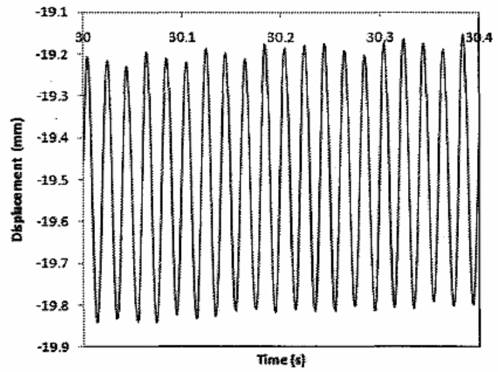

Figure 4. Displacement generated in a permanent magnet system at 213.5 rad/s by Lee et al. [8].

Comparing its performance with a dual-solenoid system, the displacement generated from a dual-solenoid system is approximately 100% higher than the permanent magnet system. In addition, despite lower power consumption by 86%, the angular frequency for a dual-solenoid system has shown to be one magnitude lower with advantage in a wider working range. With reference to Figure 3 for the plot of dual-solenoid system, it is also shown that the displacement of the mechanical oscillator is rather independent of the driving frequency.

4.3. Comparison against higher-powered dual-solenoid system

For the study of different power consumption for a dual-solenoid system, the stationary solenoid is maintained at a power rating of 0.01 Watts, for the purpose of consistency on the system environment. The variable change is the forcing solenoid, given as 2 Watts and 4 Watts. All other operating conditions remain the same throughout the experiment.

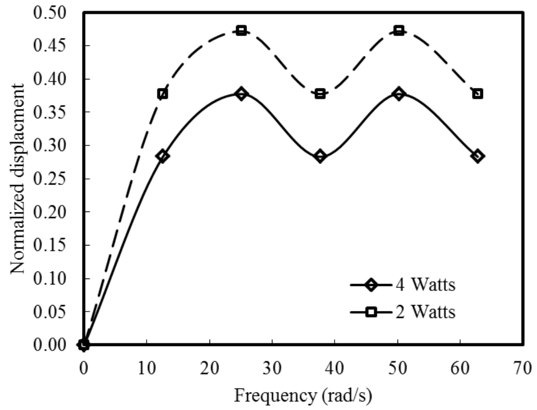

Figure 5. Comparison of a 2 Watts and 4 Watts powered dual-solenoid system.

Figure 5 shows the comparison of a higher-powered dual-solenoid system with rating of 4-Watt against a 2-Watt system. While the trend of the displacement is shown to be similar for both systems, the displacement of the 4-Watt system is shown to be relatively lower than the 2-Watt system by 10%. From Figure3-5, it may be deduced that the dynamics of the mechanical oscillator in dual-solenoid system is independent of the angular frequency. Increasing its power input to the system, while conserving the similar trend, has shown to reduce its performance by 10%. With respect to (3), it is shown that the forcing solenoid term is in negative notation hence increasing that term will eventually deteriorate the motion of the mechanical oscillator. It can then be deduced that in order to increase the performance of a dual-solenoid system, the key parameter to be altered would be the magnetic force of the stationary solenoid.A comparative performance analysis of all three systems is tabulated in Table 1. All comparative studies are made with respect to the mechanical spring system. Based on the analysis, the 2-Watt dual-solenoid has shown to have generated higher oscillation over the permanent magnet system and the 4-Watt system with significantly lower power consumption. Comparing against the mechanical spring system, although the oscillation has reported to be lesser by 62%, the power consumption, on the other hand, has shown to be more efficient by 86%.

Table 1. Performance analysis on mechanical oscillator of different systems.

Parameters	Mechanical spring (benchmark)	Permanent magnet	2-Watt dual-solenoid	4-Watt dual-solenoid
Displacement (mm)	5.3	1.0 (81% lower)	2.0 (62% lower)	1.8 (66% lower)
Power Consumption (Watts)	15	15	2 (86% lower)	4 (73% lower)

5. Conclusion

An innovative dual-solenoid electro-mechanical-vibro-impact system has been constructed and experimentally studied on the performance of its mechanical oscillator. It is observed that a dual-solenoid system generates less displacement as compared to the mechanical spring system by 62%. The dual-solenoid system, however, tops the permanent magnet system by 100% higher. The 4-Watt dual-solenoid system, on the hand, induced a lower displacement by 10% against the 2-Watt system, but topped against the permanent magnet system by 80%. The power consumption of the dual-solenoid system has proven to be more energy efficient by 86% and 73% for the 2-Watt and 4-Watt system, respectively. It is also shown that the displacement of the mechanical oscillator is independent of the angular frequency and that the stationary solenoid is the dominant parameter for the system

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