Estimated impact force for an electromagnetic hammer

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Abstract. This paper presents a force estimation of an electromagnetic hammer based on the principle of the magnetic force generated by the field of a solenoid that displaces its metal core to strike a structure under analysis. This technique known as the Hammer Impact Test is used as a method for vibration analysis. For the correct electronic system design a mathematical model for the hammer is needed to estimate impact force based on the input electrical current the hammer physical parameters.

1. Introduction
Vibration analysis is a method widely used in industry to detect failures in structures and preventive maintenance. Currently, the hammer impact test is used as a non-invasive technique, it consists of striking a structure and observing its vibrational behavior, whether it conforms to standard norms or presents some atypical characteristic [1].

Impulse excitation is a technique used in conventional vibration tests to determine the dynamic behavior of structures. The impact of a hammer is used to generate the excitation by an impulse after striking the structure. The pulse, with specific amplitude and with a minimum possible duration, can excite all vibration modes of the structure in the determined frequency range [2][3].

However, for each specific application, it is necessary to adapt the hammer model, since it must vary the impact intensity on the structure to be analyzed. In order to determine the intensity of this force at the moment of impact, this paper brings an equation for the impact force by virtue of the electric input current, having as parameters the dimensions of the solenoid and test body for the construction of the excitation system.

This paper focuses only on estimating the impact force of the hammer so that its construction is not simply empirical, but based on a previous study of the estimated force required. The purpose is to allow the design to be based on the need of the intensity of the impact force varying the pattern for the construction of the excitation structure.

2. Principle of Operation
When the system is excited by the impact of a hammer, it vibrates while the energy is dissipated. In fact, the duration time of the free vibration depends on the physical characteristics of the system, specifically the damping coefficient [4]. Figure 1 shows the schematic diagram of the electromagnetic hammer.
Figure 1. Structure of the electromagnetic hammer.

Where: \( V_e \) is voltage input; \( i \) is current input; \( H \) is magnetic field; \( F_{el} \) is elastic force; \( F_m \) is magnetic force; \( F_a \) is impact force.

2.1. **Hammer impact test**

The principle of the electromagnetic hammer is a mobile metallic core inserted inside a solenoid with one end attached to a spring. When the solenoid is triggered, it generates a magnetic force responsible for the metallic core displacement, which returns to its original position due to the elastic force exerted by the spring after the magnetic field cease [4][5].

2.2. **Magnetic force**

In general, it is widely observed the use of the magnetic field referenced to the interior or extremity of the solenoid, but in order to determine the impact force of the hammer on the tubular structure, it is necessary to first discover the influence of the produced field on the moving metallic core.

For a solenoid of length \( L \) formed by \( N \) turns with cylindrical ferromagnetic core of radius \( r \), the interior magnetic field is given by the action of the field \( H \) along the longitudinal core axis as function of the variable distance \( x \) from extremities to center of the coil as shown in figure 2.

![Figure 2. Structure of the electromagnetic hammer – core movement.](image)

The magnetic field in the middle of solenoid is given by (1):

\[
H = \frac{Ni}{2L} \left[ \frac{x}{\left(r^2 + x^2\right)^{3/2}} + \frac{L-x}{\left(r^2 + (L-x)^2\right)^{3/2}} \right] \tag{1}
\]
According to Zaro [7], the magnetic force work depends only on magnetic energy, so $U_m = F.x$. Thus the magnetic force measured in the $x$ axis direction is given by the variation of the magnetic energy along $x$ i.e., $F_x = \Delta U/\Delta x$. From this variation it is possible to find a relation for the magnetic force as function of the displacement of core from the magnetic energy, obtaining the magnetic force as function of the magnetic field $H$, the permeability of the nucleus $\mu_n$ and the permeability of the air $\mu_0$ and the area of the cylinder $A$, in the extremities ($F_{m_1}$) and the center ($F_{m_2}$) respectively by (2) and (3):

$$F_{m_2} = \frac{N^2 i^2 A \mu_0}{8(r^2 + L^2)}$$  \hspace{1cm} (2)

$$F_{m_1} = \frac{N^2 i^2 A \mu_0}{2(4r^2 + L^2)}$$  \hspace{1cm} (3)

Where: $N$ is the number of turns of the solenoid; $i$ is the input current of the system controlling the resulting impact force; $X_m$ is the magnetic susceptibility of the metal core; $\mu_0$ is the magnetic permeability of free space; $A$ is the cross sectional area of the magnetic core.

The behavior of the magnetic force must be considered to obtaining the impact force, since this occurs at the extremities of the coil, where the magnetic force is smaller, but is influenced by the center component which has the highest intensity.

2.3. Impact force

The impact force $F_a$ is obtained by the resultant forces acting on the moving core of the hammer. The resultant is given by the action of the magnetic force, due to the magnetic field to which the core is inserted subtracted from the elastic force exerted by the spring in opposition to the movement. Once $k$ is the elastic constant of the spring and $\alpha$ is acceleration of the system and is obtained from the beginning of the movement, the impact force is modeled by (4):

$$F_a = \frac{N^2 i^2 X_m \mu_0 A}{8(r^2 + L^2)} + m.\alpha - \frac{k.L}{2}$$  \hspace{1cm} (4)

In the first moment, it is observed that the body leaves the rest position, which implies in the minimum elongation after the influence of the force weight, which is balanced with the elastic force. Note it is necessary to determine the acceleration $\alpha$ that causes a additional force (second Newton’s Law), at that moment only the magnetic force acts on the moving core. That is, the body is at rest, therefore, $F_{el} = P$, so:

$$\alpha = \frac{N^2 i^2 X_m \mu_0 A}{2m(4r^2 + L^2)}$$  \hspace{1cm} (5)

Thus the expression for the impact force estimate by:

$$F_a = \frac{N^2 i^2 X_m \mu_0 A}{2} + \left[ \frac{1}{4(r^2 + L^2)} + \frac{1}{4r^2 + L^2} \right] \frac{k.L}{2}$$  \hspace{1cm} (6)

From (6) which represents the intensity of the impact force, the behavior of this force during the time was simulated in MATLAB, highlighting important parameters for characterization of the
hammer operation as: electric current intensity, magnetic core permeability, number of turns and dimensions of the solenoid and mobile core. These results are discussed in the following section.

3. Results

The results obtained were analyzed by the variation of the input current of the hammer. The behavior of the impact force \( F_a \) can be observed in time and as function of the current input, as well as other determining factors such as number of solenoid turns and magnetic permeability of the core.

To obtain the simulated \( F_a \) results, the following values were adopted for the hammer description parameters for (6): \( k = 15 \, \text{N/m} \); \( N = 300 \, \text{turns} \); \( L = 0.05 \, \text{m} \); \( r = 0.005 \, \text{m} \); \( \mu_r = 800 \). These parameters are the same as the hammer built in the laboratory in order to compare the values obtained from the force estimation and the impact measurement.

The value of \( F_a \) will follow the input current waveform \( i \). The current input signal used in this simulation was a 3.9 A amplitude pulse train and can be observed in figure 3.

![Impact force with input current of 3.9 A of amplitude in time.](image)

However, its intensity can be altered by varying the other parameters of the system such as magnetic permeability. Note that by increasing the value of the current supplied to the hammer (figure 4), keeping the other parameters constant, there is a considerable increase for the impact force, especially if \( \mu_r \) increases.

Although the behavior of the impact force depends only on the value of the input current supplied to the hammer, its intensity can be altered by varying the other parameters of the system such as magnetic permeability, number of turns and dimensions of the solenoid and ferromagnetic core.

The parameters used as reference for this model were based on the magnetic hammer already used in the [1], a compact device for the purpose of having a good performance and low power consumption for the construction of a portable scale detection system for field analysis.
Figure 4. Impact strength vs. the input current for different values of $\mu_R$.

To confirm the estimated values, the impact force of the hammer constructed with the same parameters of the simulation was measured. In the Vibration and Instrumentation Laboratory, with the aid of a PCB 086D05 load cell and an Agilent Dynamic Signal Analyzer 35670A (figure 5).

![Assembly for measuring the impact force.](image)

Figure 5. Assembly for measuring the impact force.

The experiment was performed to confirm the estimated value determined by (6). A load cell was used at the hammer impact point so that it was possible to capture the maximum force exerted by the force. A impulse excitation was applied in input and the measurement result was an inertness force peak of 25.78 N. In figure 6 it is possible to observe the peak value obtained with the impact of the hammer.

The value of the peak impact force obtained using the modeled hammer through (6) was 25.72 N for an input current of 3.9 A, it was the current consumed by the hammer during the measurement, considering 12 V DC power supply, while in the experimental measurement for the hammer constructed this value was 25.78 N. The error obtained was 0.233 %.
Figure 6. Impact force measurement.

Note that, although the maximum value of the impact force is close to the estimated one, there are some minor peaks present. These values should contain a secondary impact from the first strong impact hammer in the structure. The metallic core after collide the structure generates backward thrust, but the magnetic field, still active, pulls back the metal core again for another less intense impact. This undesired effect can be corrected by decreasing the duration of the impulse excitation.

4. Conclusions
The objective was reached since the results obtained were within expected, the obtained error was close to zero and the measured value was very close to the expected one. With these results, it is now possible to build an impact hammer by molding its dimensions according to the desired force instead to test many different methods of building a hammer in order to find the best, avoiding trial and error.

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