

Magnetic gauge for free surface velocities in reinforced concrete blasted by explosives

Y Ashuach, I Gissis and C Avinadav

Rafael Advanced Defense Systems, Ltd., P.O.Box 2250, Haifa 3102102, Israel

E-mail: ahezi@rafael.co.il

Abstract. We developed a simple magnetic gauge for measuring free surface velocities of rock materials in the range of 0.1-20 m/s. The gauge consists of two elements: a NdFeB magnet and a pick-up coil. The coil is attached to the free surface at the point of interest. The magnet is placed a few centimeters away from the coil and the rock. The motion of the rock surface, due to blast loading, induces current in the coil due to the changes in the magnetic flux. The coil velocity is deduced from the measured current using a computational code. The gauge was tested and validated in a set of free-falling experiments. We present velocity measurements from various blast experiments in limestone and reinforced concrete, using both the magnetic gauge and a Doppler interferometer. The results obtained from the two measurement techniques are in good agreement. Since the magnetic gauge is cheap and very simple to operate, it is well-suited for mapping the velocity distribution at multiple points of interest on the concrete surface.

1. Introduction

Design of protected structures should take into account the scenario of explosions that occur just outside their external walls. Such explosion may damage the internal side of the walls by forcing it to move at a velocity which is higher than a threshold velocity which marks the failure of the wall structure. Reinforced concrete and rock materials can withstand different levels of imposed velocities, and should be characterized in order to estimate the safety factor and the structure durability against different threats. Numerical simulations are a key tool for such safety evaluations. Thus, proper constitutive models should be calibrated for the relevant materials.

We present a magnetic gauge which was developed to measure the free surface velocities of reinforced concrete or rock materials in blast experiments. The gauge consists of a coil wire which is epoxied to the moving surface, and a permanent magnet which must stay at rest during measurement time. The relative velocity between the two elements induces an electrical current in the coil due to the change in the magnetic flux. Our goal is to measure velocities of the order of a few meters per second, which are the typical thresholds for the failure of reinforced concrete structures [1]. The required measurement times are a few tens or hundreds of microseconds. The gauge was designed to be as simple and cheap as possible, in order to enable multiple points of velocity measurement in blast experiments. We present the results from free falling and small-scale blast experiments with magnetic gauges. The measurements were compared with PDV results and showed very good agreement.

2. The magnetic gauge

The magnetic gauge is presented schematically in figure 1.



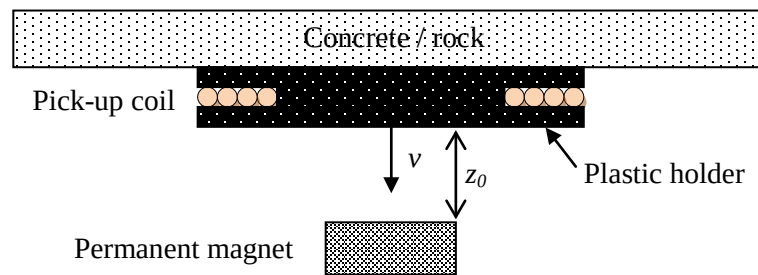


Figure 1. Schematic description of the magnetic gauge.

We used pick-up coils with 25 turns of thin copper wire assembled on a 40 mm diameter plastic holder. The plastic is epoxied to the free surface. The permanent magnet is a 25 mm-diameter, 10 mm-thick, NdFeB magnet. The initial magnet-coil distance limits the duration of the measurement, larger initial magnet-coil distances allow longer measurement times. However, if the distance is too large, the onset of the signal becomes indistinguishable due to poor signal to noise ratio. We found that for the relevant velocities, placing the magnet a few centimeters away from the coil provides reasonable signals. For the ease of velocity calculations, the magnet and the coil should be concentric and placed along the assumed flight direction, *i.e.*, normal to the free surface.

2.1. Surface velocity calculations

In order to calculate the relative velocity, one needs to know the spatial distribution of the magnetic field, *i.e.*, $B(r,z)$. Therefore, we measured the magnetic field of the magnet and found its magnetization using a Comsol model. As the coil flies toward the magnet, it experiences an induced voltage [2] due to change in the magnetic flux Φ according to

$$\varepsilon = \frac{d\Phi}{dt} = \frac{d\Phi}{dz} \cdot \frac{dz}{dt} = v_z \cdot \frac{d\Phi}{dz}. \quad (1)$$

Using the measured signal, the coil velocity is calculated in small time steps dt . In each time step we take into account the temporary coil-magnet distance z_i and extract the velocity using

$$v_i = \varepsilon_i / \left(\frac{d\Phi}{dz}(z_i) \right), \quad (2)$$

where ε_i is the voltage measured by the digitizer at time step t_i . In the first step we use $z_i = z_0$, where z_0 is the initial coil-magnet distance. After each step we find the new coil-magnet distance using

$$z_{i+1} = z_i - v_i dt. \quad (3)$$

The measurement ends when the coil holder hits the magnet, or when the magnet starts moving due to arrival of stress waves from the source of the blast.

2.2. Extending the measurement duration

The measured signal is due to the relative velocity between the pick-up coil and the magnet. Therefore, the measurement is incorrect after the magnet starts moving, either due to collision with the moving coil or the arrival of sound waves from the blast through its mounting device. In a typical experiment we wish to measure velocity for at least a few hundreds of microseconds. Therefore, in our experiments we use wave delaying mounts such as the one shown in figure 2. The geometry of these specially designed mounting devices forces the sound waves, arriving from the moving wall, to travel a long distance before reaching the magnet. Moreover, they are made from lightweight cross-linked polyethylene foam, which has a low sound velocity (around 500 m/s).

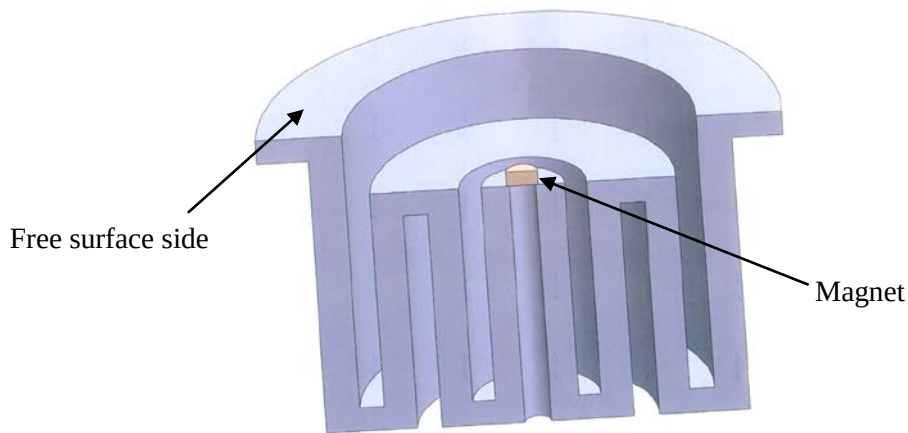


Figure 2. The structure of the wave delaying mounting device.

3. Experimental

3.1. Free fall tests

First, we performed a series of tests where the coil was dropped from different initial heights toward the magnet. Some raw signals obtained in such tests are shown in figure 3a. The velocities extracted from these measurements agree well with those calculated using the law of gravity. The peak voltages are a linear function of the magnet velocities, as shown in figure 3b.

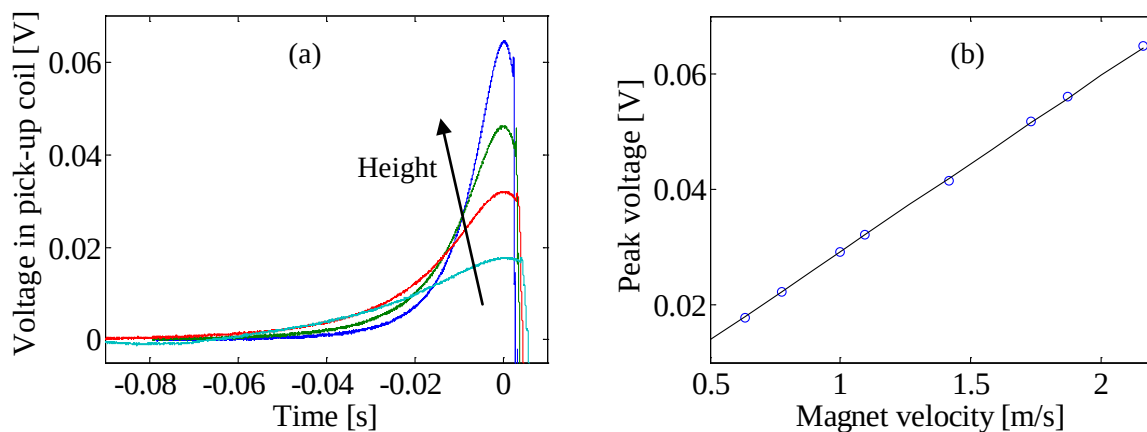


Figure 3. a) Magnetic signals obtained in a series of free fall tests from different heights; b) the linear relationship between the peak voltage and the peak magnet velocity.

3.2. Blast experiments

We performed a series of blast experiments with 50-100 grams of RDX-based explosive charges confined in $1\text{ m} \times 1\text{ m} \times 0.75\text{ m}$ blocks of reinforced concrete and rock materials. We drilled a hole from the upper face and inserted the explosive charge to the center of the block (see figure 4). On the bottom face of the block we mounted some magnetic velocity gauges, at several distances R from the center of this face. The results of the free surface velocity measurements are shown in figure 5a. The velocities are of the order of a few meters per second. The peak velocity decreases with the distance of the measurement point from the explosive charge. The velocity measurements are valid for several hundreds of microseconds. Afterwards, the motion of the permanent magnet due to arrival of the sound waves reduces the relative velocity.

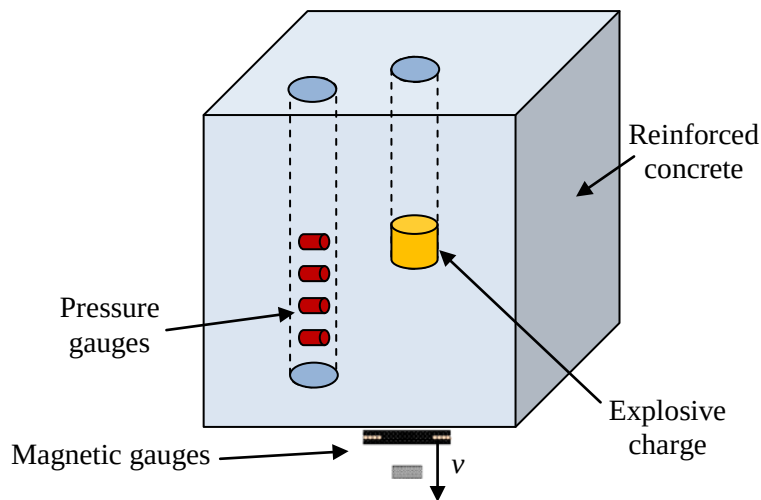


Figure 4. Schematic geometry of the blast experiments.

To achieve better characterization of the reinforced concrete behaviour, we measured the pressures at different distances from the explosive using in-situ carbon resistors as shown in figure 4. The carbon resistors were calibrated in a previous work [3]. The pressure gauges were mounted on a steel tube that was inserted to another drill in the upper face of the block. The gauges were connected to the digitizer using low-noise cables. The coupling medium between the gauges and the reinforced concrete bulk was Sika non-shrink grout. Figure 5b shows the pressure signals from these resistors. The signal duration is between 20-40 μs , due to the dimensions of the explosive charge. The peak pressures are of the order of 0.6-1 kbar, and decrease with the distance from the explosive. The measured velocities and pressures were used to calibrate a constitutive model for the reinforced concrete using numerical simulations.

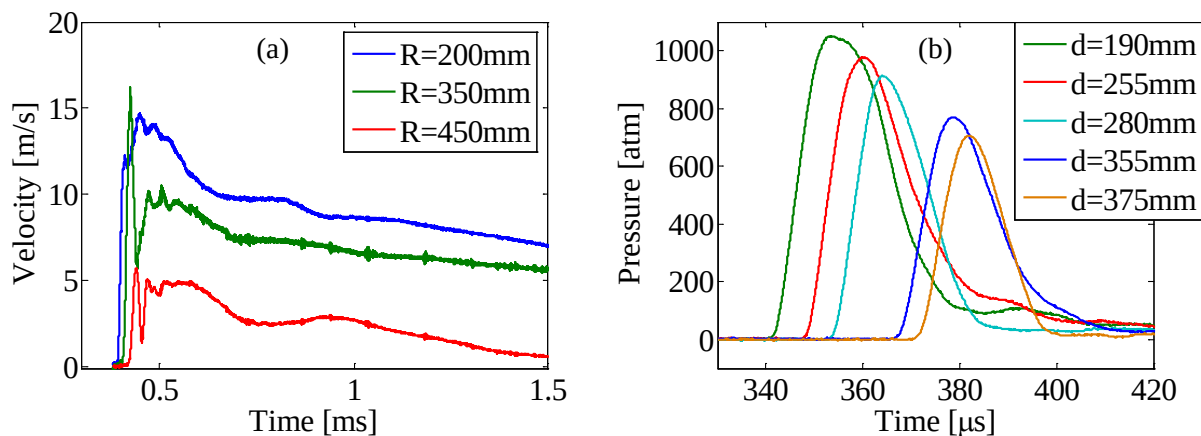


Figure 5. a) Free surface velocities measured at locations with different radii R on the bottom face of the rock block; b) pressures measured by carbon resistors at different distances d from the explosive.

In order to validate the accuracy of the magnetic measurement, we performed an experiment with additional PDV probes [4] located at the same distances from the charge as the magnetic gauges. The agreement between the results obtained from both methods was within 5-10%, as shown in figure 6.

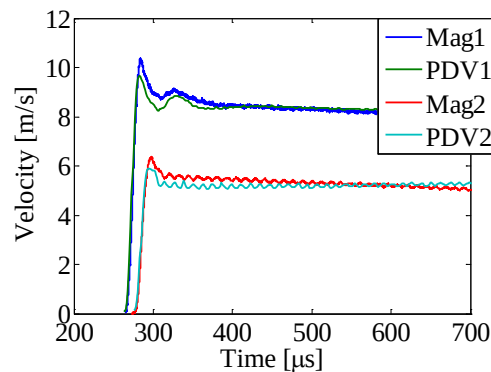


Figure 6. Velocities measured by magnetic gauges and PDV probes at equivalent positions.

There are two significant factors which determine the accuracy of the magnetic measurements. The first is the initial coil-magnet distance z_0 . Due to the inverse dependence of the magnetic field on the distance from the magnet, the uncertainty in z_0 results in a systematic error in the extracted velocities, which is larger as the magnet is initially closer to the coil. The second factor is the concentricity and parallelism of the coil and the magnet. Deviation from ideal orientation leads to incorrect velocities which are extracted from the signal. Velocity calculations with non-concentric gauge elements, or when the movement direction is not normal to the surface, are more complicated and beyond the scope of our simple model.

3.3. Inverted gauge

We also tried a simpler assembly of the gauge elements which consists of a moving magnet and a pick-up coil at rest. However, the signals obtained with such inverted gauge were inconsistent with previous results. Figure 7a shows free surface velocities measured using inverted gauges. The velocity profiles in this figure are almost constant, unlike the signals shown above in figure 5a. The reason for this behavior is the spallation formed in the concrete, a few millimeters from the surface. This is evidenced in small pieces of concrete which were found attached to the magnets after the experiment. This phenomenon can be the result of the large weight of the magnet, which locally reduces the velocity, as compared with its surroundings, forming shear failure. Thus, in this case, the magnet keeps flying at its initial velocity rather than following the moving surface. In order to verify our conclusion, we performed PDV measurements of the magnet surface and the concrete adjacent to it. The results shown in figure 7b indicate that whereas the surface decelerates, the magnet keeps moving at a constant velocity. Therefore, the positions of the pick-up coil and magnet are non-interchangeable.

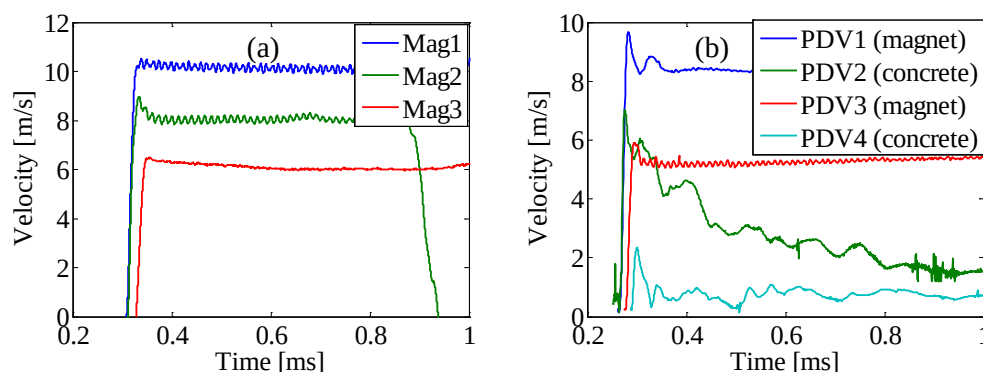


Figure 7. a) Free surface velocities measured by several inverted magnetic gauges, *i.e.*, with the magnets as the moving elements; b) velocities of the permanent magnet and the free concrete surface close to the magnet, as measured by PDV.

4. Conclusions

We developed a magnetic gauge to measure free surface velocities of blast loaded reinforced concrete and rock materials of the order of few meters per second. We tested the gauge in various small-scale blast experiments and achieved very good agreement with results obtained from interferometric measurements (PDV). The gauge is very simple and cheap, enabling measurement of multiple points of interest at the same experiment. Dynamic velocity measurements allow for the calibration of constitutive models for these materials.

References

- [1] Jiken K 1986 *Proc. of the Int. Symp. on Intense Dynamic Loading and its Effects (Beijing, China, June 3-7, 1986)* ed Z Zheng and J Ding (Beijing: Science Press) pp 911-15
- [2] Jackson J D 1999 *Classical Electrodynamics, 3rd ed.* (New York: John Wiley & Sons)
- [3] Rosenberg Z, Ginzburg A and Ashuach Y 2007 *Int. J. Impact Engng.* **34** 732-42
- [4] Strand O T 2006 *Rev. Sci. Instrum.* **77** 083108