Instrumentation and Data Acquisition for Dynamic Testing of Ground Support

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***Abstract*— The Spokane Mining Research Division (SMRD) of the National Institute for Occupational Safety and Health has recently developed a dynamic testing machine that imparts a controlled shock to a ground support test panel in order to investigate the effects of seismic loading on the material. Dynamic testing is critical for understanding the mechanical response of ground support used in seismically active locations of a mine. In the past, dynamic testing of ground support has generally been somewhat qualitative, but currently more quantitative testing is being employed. This paper describes the sensors and data acquisition system used to record the dynamic measurements of the shock tests performed by SMRD. It includes a discussion of sensor selection and installation to serve as an initial guide for future research. Testing of ground support and its response to dynamic loading can lead to developments that improve mine worker safety in seismically active underground mines. (*Abstract*)**

Keywords—dynamic testing, shotcrete

I. Introduction

The Spokane Mining Research Division (SMRD) of the National Institute for Occupational Safety and Health (NIOSH) has repurposed a general purpose MTS IMPAC 3636 Mark II shock test machine to perform dynamic testing of reinforced shotcrete surface support materials. Reinforced shotcrete is a common rock support material that combines shotcrete with reinforcing materials to form a composite support. Unreinforced shotcrete has high initial strength and adheres to rock, which makes it useful to hold loose rock from spalling and raveling from the excavation, but load capacity diminishes after only a few millimeters of flexural displacement. Steel reinforcement such as wire mesh adds high ductility, allowing strength to be maintained over displacements exceeding 10 cm. The dynamic test machine is intended to provide correlation between established quasi-static testing methods and more recent dynamic testing based on momentum transfer principles (Player et al., 2004) in order to understand the behavior of reinforced shotcrete subjected to dynamic loading. The machine allows researchers to study a range of extreme rates of strain and high g-forces that are associated with seismic loading such as those from rockbursts caused by overstressed rock or fault slips. A recent paper describes the results of preliminary experiments with this testing machine (Raffaldi et al., 2017). The present paper describes the retrofit of the IMPAC machine with modern accelerometers, linear encoders, and pressure transducers and shows the steps in post-processing of the data. The end result of the research is to be able to predict the performance of the support materials to mitigate or lessen the severity of rock bursts.

II. Description of Test Apparatus

The mechanical components of the dynamic test machine are shown in Figure 1. The heart of the machine is a one meter square shock table upon which concrete test panels are attached. In operation the shock table is raised upon 7.62 cm diameter, 4 meter long guide rods with hydraulic lift cylinders to a given drop-height upon which pneumatic brakes are applied to hold the shock table before release. The lifters are first retracted before the pneumatic brakes are released allowing the shock table to fall. The shock table collides with four elastomer pads attached to a large 4000 kg metal block called the seismic mass. The seismic mass is then slowed by hydraulic-pneumatic accumulators attached to it, the end result being mechanical shock applied to the test panel. The test sample is drilled in each corner to rest on mating pins of the shock table. Located above the test panel is a 38.1 cm diameter hemispherical loading mass. This loading mass is constrained horizontally by another set of 3.81 cm diameter, 76.2 cm long guide rods attached to the shock table and imparts an external load to the test sample via momentum-transfer. This additional load simulates the action of loosened rock ejecting from the excavation between rock bolts during a seismic event.

As shown in Figure 2 are the location of the new sensors attached to the test machine. These sensors measure acceleration, displacement, and hydraulic pressure and are divided into three sections; shock table, loading mass, and seismic mass. Displacement of the shock table is measured with an inductive linear encoder (Figure 3). The encoder reader head is attached to the shock table and contains a hole through which a 15.24 mm diameter, 2.80 m long stainless steel scale tube is passed. The scale tube constrains Sphersoyn™ high-precision nickel-chrome ball bearings which changes the magnetic field of the reader head to provide precise position information. The scale tube is mounted at each end to the support frame parallel to the guide rods. Accelerations of the four corners of the shock table are sensed with piezoelectric accelerometers (Figure 4).

Likewise, the hemispherical loading mass is mounted with sensors to measure loading mass displacement and acceleration. Displacement is measured with two linear magnetic encoders attached to both of the shock table guide rods as shown in Figure 5. These encoders are composed of a flat magnetic tape and free floating read heads. The read head interpolates the magnetic field sensed at its face generating a series of quadrature digital pulses output to the datalogger. The magnetic tape is mounted upon a face milled out of the slide bar while the read head is mounted in a slot milled into the pillow block bearing maintaining a 2 mm separation between the read head and the magnetic tape. Aligning the sensor back flush to the outside surface of the pillow block ensures that the sensor is within the 3º pitch and 1º yaw tolerance specification. (Note: that currently only one sensor on the loading mass is recorded by the data acquisition system due to channel limitations.) Acceleration is measured with a piezoelectric accelerometer mounted above the center of mass of the hemisphere.

The seismic mass is mounted with sensors to measure seismic mass displacement, seismic mass acceleration and accumulator pressure. Displacement is again measured with an inductive linear encoder (Figure 6) mounted to the seismic mass and base of the machine. The encoder reader head is mounted to the seismic mass while the round 5.75 mm diameter, 75 cm long carbon fiber scale is mounted to the baseplate of the dynamic test machine, passing through a hole in the reader head attached to the seismic mass. Acceleration is again sensed with a piezoelectric accelerometer mounted at the top-center of the mass while the piston pressure is sensed with an analog output pressure transducer (Figure 7).

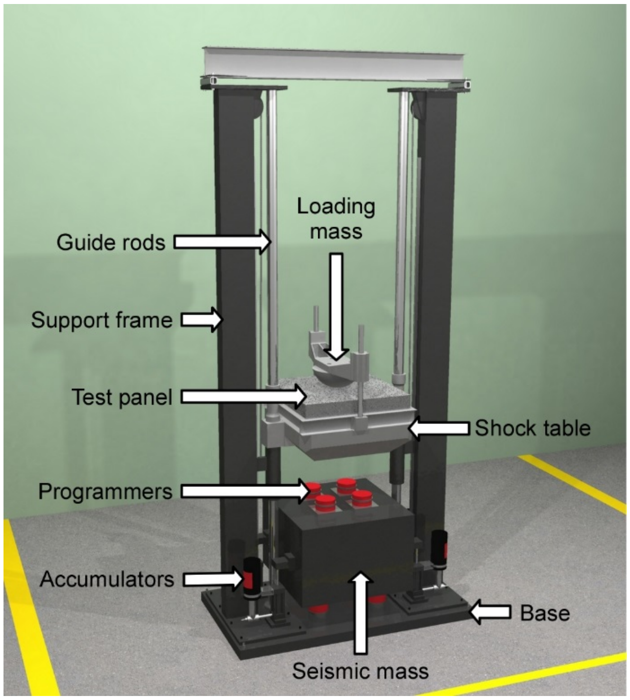

Fig. 1. Schematic of dynamic shock test machine

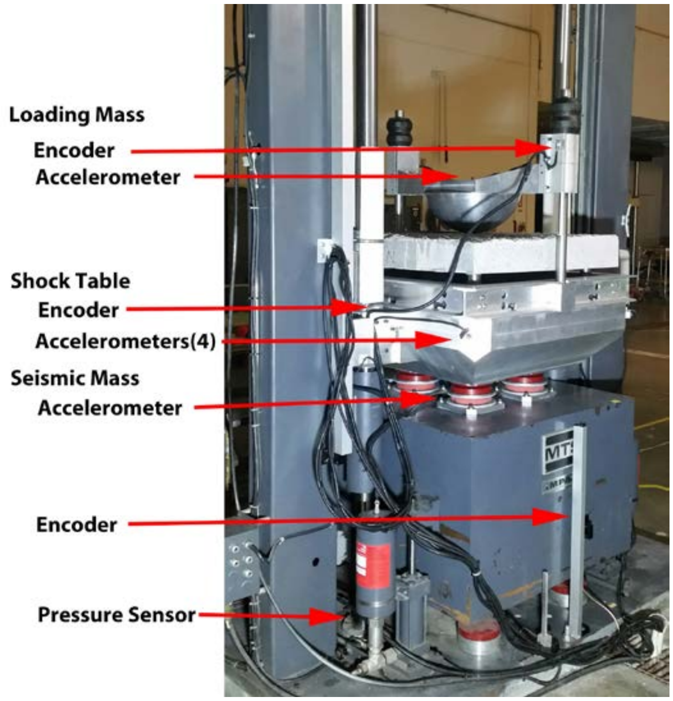

Fig. 2. Dynamic shock test machine sensor locations

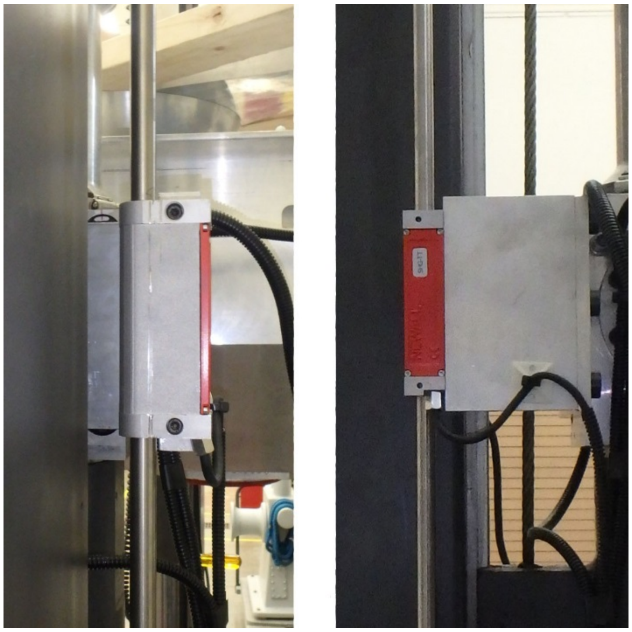

Fig. 3. Shock table displacement sensor (left: side view, right: end view)

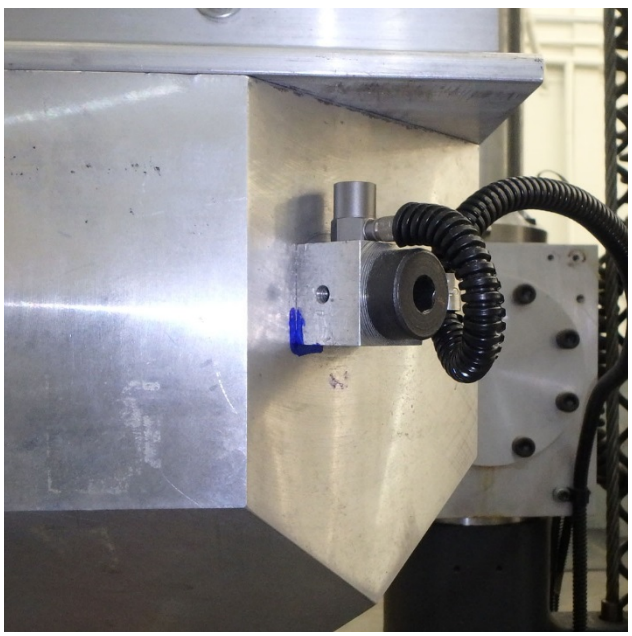

Fig. 4. Accelerometer mounted to one corner of the shock table

Fig. 5. Loading mass displacement sensor composed of magnetic scale and read head

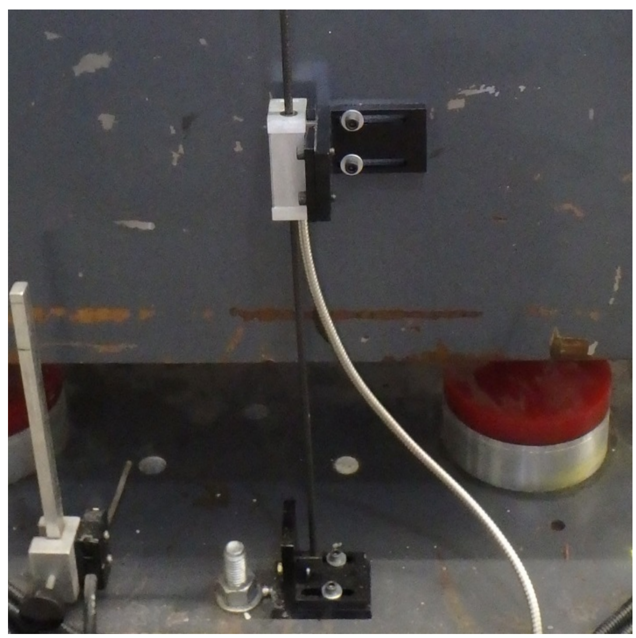

Fig. 6. Seismic mass inductive displacement sensor

Fig. 7. Pressure transducer in accumulator damper circuit

III. MEASUREMENT OF DISPLACEMENT

Displacement is measured with the inductive and linear magnetic incremental encoders shown in Table 1. Inductive linear incremental encoders are used to measure displacement on the seismic mass and shock table. These sensors provide more than adequate resolution for tests being conducted, they can be operated at the required velocities and be able to withstand the accelerations developed during the tests (Nyce, 2004). Inductive linear encoders are composed of a reader head and scale. The scale is composed of a series of high-precision nickel-chrome ball bearings inserted into the stainless steel or carbon fiber tube end-to-end along the length of the scale. The reader head contains a primary coil where a 10 kHz sinusoidal current is induced that generates an electromagnetic field which interacts with the nickel chrome precision balls contained in the scale. As the head moves along the scale a set of four pickup coils detect variations in the induced field that are then combined and processed by the electronic circuitry to generate a signal that varies as the head moves along the scale. Depending on the position of the reader head as it passes over each ball, the phase shift of this pickup signal relative to the drive signal will vary between 0° and 360° and outputs the data as a series of quadrature TTL digital pulses.

A linear magnetic encoder is used to measure the displacement of the loading mass. Linear magnetic encoders are also composed of a read head and scale though in this case the scale is composed of a series of magnetic poles end-to-end along the length of the scale. As the read head moves along the scale it interpolates the magnetic field strength detected between poles generating a series of quadrature digital pulses. Cable length exceeded the maximum 3 meter distance specified by the manufacturer for single ended open collector output so the sensors were ordered with RS422 differential outputs. A suitable off-the-shelf converter was not found to bridge the RS422 sensor to the single ended TTL input of the data acquisition system so a custom circuit board was fabricated to hold a MAX14891EATP+ device from Maxim Integrated Products™. This device has four inputs so will convert both displacement sensors mounted on the loading mass slide bars and will operate in excess of the 8.3 MHz maximum pulse rate specified by the encoder manufacturer.

At a maximum drop height of 2 m, the shock table will develop a velocity of 6.3 m/s, more than sufficient to simulate typical rock bursts (Raffaldi, 2017A). The encoders may be operated up to at least 20 m/s satisfying the velocity requirement. The sensors attached to the shock table and loading mass can experience up to 100g of acceleration during the experiment. The shock table sensor meets this level of shock resistance though the loading mass sensor is only rated to 30g. A suitable replacement for the loading mass displacement sensor will be specified for future tests.

TABLE I. LINEAR POSITION SENSORS

Location	*Sensor*	*Resolution /Accuracy*	*Max Velocity*
Shock Table	Newall SHG-TTSCTE	5 um/ +/- 10 um	20 m/s
Loading Mass	RLS LM15-ICD20A	25 um/ +/- 25um	42 m/s
Seismic Mass	Newall MHG-TTVFSA	10 um/ +/- 10 um	20 m/s

IV. MEASUREMENT OF ACCELERATION

Accelerations are measured with IEPE (Integrated electronic piezoelectric) accelerometers. This type of sensor is well suited for the fixture and is commonly used in shock and vibration experiments (Walter, 2008). The IEPE circuit converts the high impedance signal from the piezoelectric sensing element into a usable low impedance voltage signal used to drive the data acquisition system. The data acquisition system must be equipped with IEPE signal conditioning circuits and biased correctly for the application. PCB model 352C03, 500g accelerometers were specified for the shock table and loading mass, while a PCB model 352C33, 50g accelerometer was specified for the seismic mass. They have a 3dB high pass cutoff frequency of 0.5 Hz and self-resonant frequency of 50 kHz. The bandwidth of the data acquisition system was limited to 5 kHz to reduce the high frequency noise present around resonance.

V. MEASUREMENT OF PRESSURE

Hydraulic pressure in the piston accumulator attached to the seismic mass can reach a maximum of 5000 psi. This pressure is measured with a general purpose Omega Instruments PX309-5kG5V strain gauge pressure transducer with a 2% accurate 5V analog output.

VI. DATA ACQUISITION

An HBM Genesis data acquisition system was repurposed, for convenience, from past research to serve as the datalogger for the machine (Johnson, 2009). Two four-channel GN441 analog input modules convert the signals from the IEPE accelerometers and the pressure transducer. A GN6470 digital input module converts the quadrature signals from three encoders, one each from the shock table, loading mass, and seismic mass. Shock pulses ranging from 5 to 30 ms can be delivered to the shock table by changing the elastomer pads with ones of different durometer and thickness. A sufficient sample rate is required in order to accurately represent the signal in the time domain, reduce high frequency noise, and keep data file size manageable.

To reduce high frequency noise in the accelerometers the 3-dB cutoff of the low-pass anti-aliasing filter was chosen to be 5 kHz. The reciprocal of this frequency is approximately 25 times higher than the minimum pulse width (5 ms) ensuring accurate sampling (Walter, 2008). The minimum sampling rate of a GN441 module, which implements a 5 kHz low pass filter, is 20 kHz. This sampling frequency was used throughout testing performed on the machine. Displacement transducers were also recorded at a 20 kHz word rate. Internally, the GN6470 samples the quadrature inputs at 10 MHz and updates a counter. This counter is read at a 20 kHz rate and stored to memory along with the analog inputs. Figure 8 shows a typical response of an experiment.

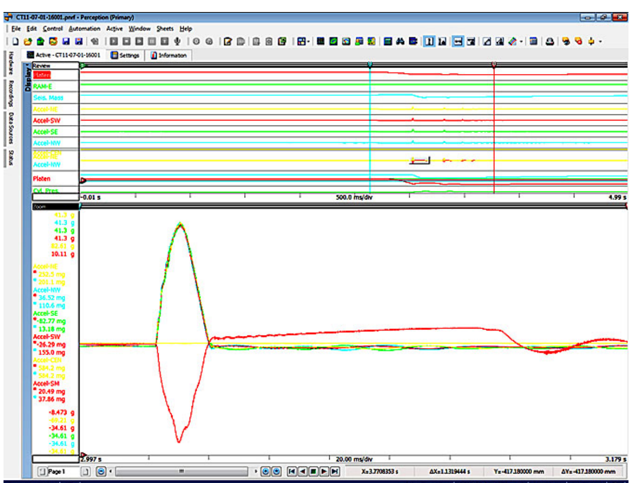

Fig. 8. Data acquisition screenshot using Perception software

VII. POST PROCESSING

Data from the data acquisition system is exported to comma delimited files for post processing in MATLAB® and Signal Processing Toolbox™. The MATLAB script filters the accelerometer signals, computes rise, fall, and pulse duration times of the accelerometer signals, and computes velocities from the displacement sensors. Accelerometer signals are filtered with a zero phase symmetric 40 tap FIR filter as shown in Figure 9. The filter coefficients are generated with MATLAB function “maxflat” and filtering is performed with MATLAB® function “filtfilt.” The function “filtfilt” performs both forward and reverse direction filtering to remove the group delay of the filter allowing the filtered and raw signals to overlap in time. The cutoff frequency of the FIR filter is adjusted iteratively, within the range of 1 to 4 kHz, so that the filtered signal visually tracks the raw signal (Figure 10). Ten to ninety percent rise and fall times, and ten to ten percent pulse width are calculated for the acceleration pulse automatically by the script.

Each encoder signal is differentiated in order to provide an estimate for velocity. In MATLAB this is accomplished by first reducing the quantization noise of the encoder data with a sixth order, 1 kHz, analog Butterworth filter, again with application of MATLAB function “filtfilt” (Figure 11). After filtering, the signal is differentiated with first order MATLAB function “diff” and prepended with a leading zero (to make equal length vectors) yielding an estimate of velocity that is time aligned with the displacement data. Figure 12 shows a typical displacement response while Figure 13 shows a typical velocity result.

```
Fs = 20000; % Sampling Frequency
N  = 40;    % Order
Fc = 1000;  % Cutoff Frequency
[b,a,b1,b2,sos_var,g] = …
maxflat(N, 'sym', Fc/(Fs/2));

B=filtfilt(sos_var,g,A);
%vector A contains raw data
```

Fig. 9. Accelerometer processing in MATLAB

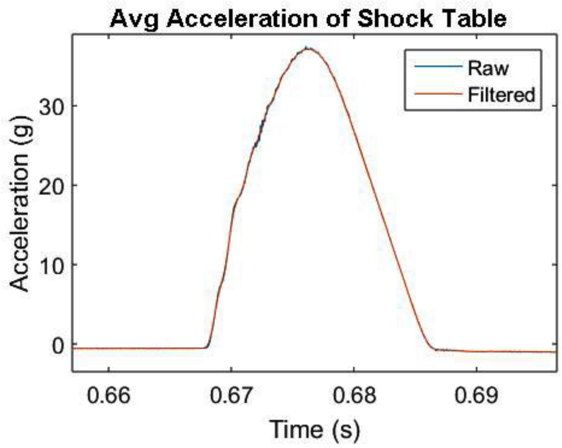

Fig. 10. Acceleration versus time shock pulse (filtered average of 4 corners of shock table)

```
Fs = 20000; % Sampling Frequency
N  = 6;     % Order
Fc = 1000;  % Cutoff Frequency
[fb,fa]=butter(6,Fc/Fs/2);
% create the filter coefficients
B=filtfilt(fb,fa,A);
% vector A contains the raw data
C=diff(B./Fc);
% differentiate
D=vertcat(0,C*Fs);
% convert to meters/second
% append leading 0
```

Fig. 11. Linear position encoder processing in MATLAB

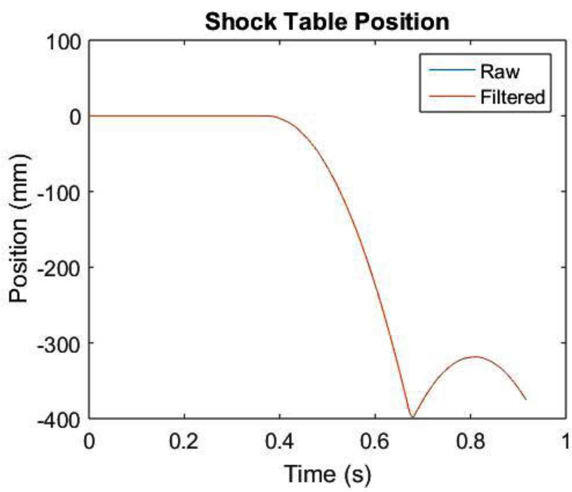

Fig. 12. Shock table displacement versus time (from measurement)

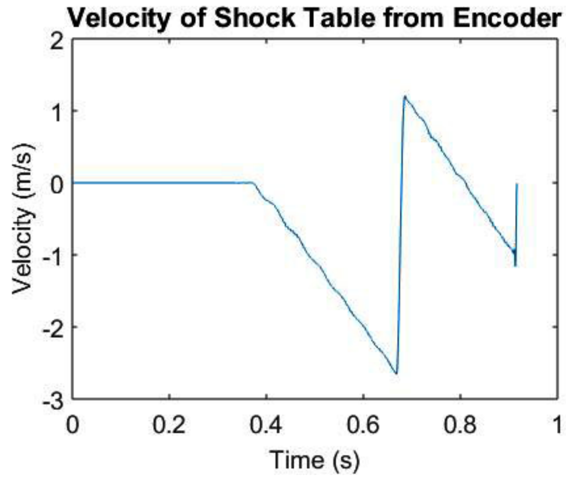

Fig. 13. Shock table velocity versus time

VIII. CONCLUSION

Careful specification and processing of sensors for the dynamic testing machine at SMRD have produced high quality data that is used by researchers to estimate the strength of various shotcrete materials under a dynamic seismic load. This understanding will eventually provide guidance to mine operators on the appropriate ground support materials to apply to mine tunnels in seismically active areas of a mine. The end result of appropriate application of shotcrete support materials is to prevent physical injury to mine workers during a seismic event.

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DISCLAIMER

Use of trade names and commercial sources is for identification only and does not imply endorsement by NIOSH, the Centers for Disease Control and Prevention, or the U.S. Department of Health and Human Services. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of NIOSH, the Centers for Disease Control and Prevention, or the U.S. Department of Health and Human Services.

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