Non-Intrusive Shock Measurements using Laser Doppler Vibrometers

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ABSTRACT

Stud mount accelerometers are widely used by the aerospace industry to measure shock environments during hardware qualification. The commonly used contact-based sensors, however, interfere with the shock waves and distort the acquired signature, which is a concern not actively discussed in the community. To alleviate these interference issues, engineers at the Jet Propulsion Laboratory are investigating the use of non-intrusive sensors, specifically Laser Doppler Vibrometers, as alternatives to the stud mounted accelerometers. This paper will describe shock simulation tests completed at the Jet Propulsion Laboratory, compare the measurements from stud mounted accelerometers and Laser Doppler Vibrometers, and discuss the advantages and disadvantages of introducing Laser Doppler Vibrometers as alternative sensors for measuring shock environments.

KEY WORDS: Shock testing, Laser Doppler Vibrometer, LDV, accelerometer

INTRODUCTION

Shock events during launch and other mission operations are often severe and can lead to catastrophic failures. Shock testing is therefore a critical step in qualifying flight hardware and meeting environmental requirements. To ensure a successful shock test, engineers rely on measurements from accelerometers mounted on or near the hardware. These contact-based sensors, however, have limitations in providing accurate measurements of shock environments. Specifically, stud mounted accelerometers interfere with the high-frequency shock waves and distort the acquired signature. Surface mounted accelerometers have also been found to have an upper frequency limit of approximately 20 kHz due to calibration limitations and physical interferences with the structural response at high frequencies (Walter 2008). Obtaining structural response measurements of sensitive surfaces such as optical hardware or small devices such as Microelectromechanical systems (MEMS) is also problematic with surface mounted accelerometers.

Optical sensors, such as Laser Doppler Vibrometers (LDVs), offer a range of opportunities in shock tests and analyses compared to the more traditionally used accelerometers. LDVs provide a non-intrusive measurement technique as they do not require contact with the moving surface. Thus, shock response measurements of hardware interfaces, optically sensitive surfaces, and small devices are possible, and interferences with the shock waves and acquired signature are eliminated.

Shock simulation tests have been completed at the Jet Propulsion Laboratory (JPL) using LDVs and stud mounted accelerometers. The measured shock responses have been compared to determine the feasibility of using LDVs as alternative sensors in future shock testing.

LASER DOPPLER VIBROMETERS

Laser Doppler Vibrometers are optical sensors that measure the dynamic response of moving objects (fluids, solid structural surfaces, etc.) by measuring the instantaneous velocity along the laser line-of-sight (Drain 1980). LDVs are essentially interferometers that measure the Doppler shift of scattered light coming from the vibrating object (Castellini, Reve, and Tomasini 2009), and the velocity is found using the following equation:

$$\Delta f_D = \frac{2v}{\lambda} \tag{1}$$

where Δf_D is the frequency shift, λ is the laser wavelength, and v is the object velocity. This measurement is based on the laser Doppler technique introduced in 1964 by Y. Yeh and H.Z. Cummins (Yeh and Cummins, 1964), and it offers a non-intrusive method for capturing dynamic responses of structures.

A variety of LDV systems have been developed to measure out-of-plane, in-plane, differential, and torsional vibrations. Scanning LDV (SLDV) systems are also widely used to collect rapid point by point measurements of large surfaces with high spatial resolution and low testing time (Castellini, Martarelli, and Tomasini 2006). These systems provide a number of opportunities compared to surface mounted accelerometers, including measurements of structures that could not otherwise be captured due to sensitive surfaces, size, mass, or operating conditions. LDV systems also allow for reduced setup and testing time, position flexibility, and no mass-loading affects.

SHOCK SIMULATION TESTS

Simulated pyroshock testing is conducted at the JPL Environmental Test Laboratory (ETL) using a tunable resonant beam shock apparatus (Figure 1). This apparatus, which was derived from a similar system at Sandia National Laboratory (Davie and Bateman 1997), uses gas pressure and a projectile to excite the clamped beam and transmit a shock pulse to the attached test fixture and hardware.

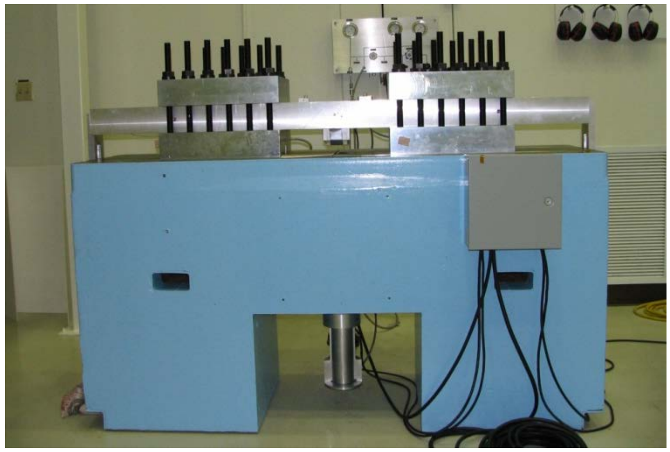

Figure 1: Tunable Resonant Beam Shock Apparatus, Environmental Test Laboratory, Jet Propulsion Laboratory.

Two shock simulation test campaigns have been completed to demonstrate the use of LDV sensors in shock testing. The first test campaign was completed in March 2011 (Figure 2). The test article was an aluminum strike plate attached to a 10 inch magnesium cube typically used for mounting flight hardware to the tunable beam. An accelerometer, fixed-point LDV, and SLDV were used to measure the shock response of the strike plate orthogonal to the shock impulse axis. These three sensors were positioned to measure approximately the same location of the strike plate. The SLDV system was also used to record the data from all three sensors. The scanning capabilities of the SLDV have not yet been explored for this application.

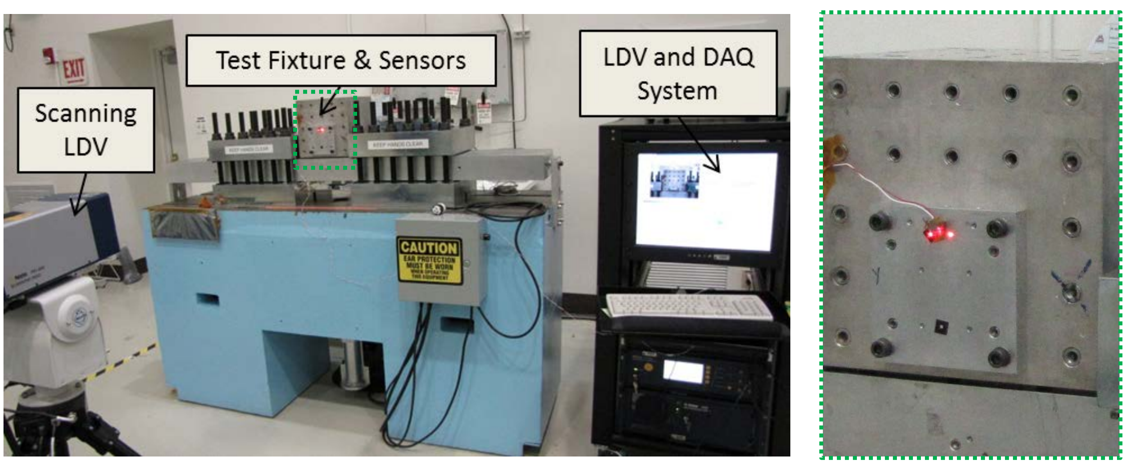

Figure 2: Shock simulation tests on aluminum strike plate using two Laser Doppler Vibrometers and one accelerometer.

Two identical runs were completed with an approximate gas pressure level of 50 psi. Results of these runs are provided in Figure 3 and Figure 4. Figure 3 shows the time histories of the three sensors in velocity and acceleration units. Figure 4 shows the Fast Fourier Transform (FFT) and Shock Response Spectrum (SRS) of the three sensors in acceleration units. These plots show good correlation between the three sensors. There are also differences in the responses that have interesting implications. In the SRS plot (Figure 4, right), for example, the accelerometer measurement shows a higher SRS between 100 and 200 Hz whereas the LDV measurements show higher SRSs between 500 and 10,000 Hz. As the sensors could not be positioned at the exact same location on the strike plate, this could explain some differences in the measured responses.

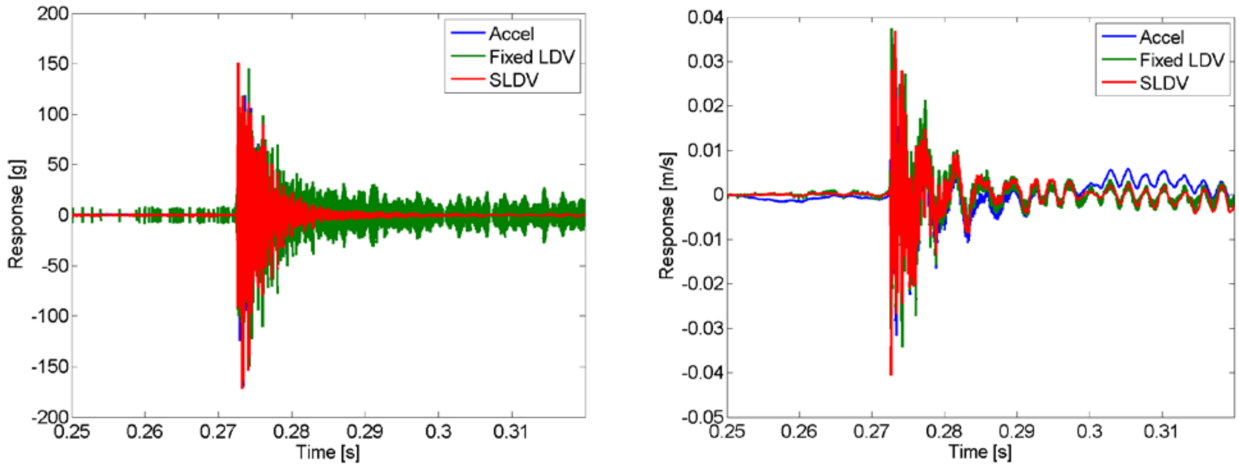

Figure 3: Time history data of aluminum strike plate: acceleration units (left), velocity units (right).

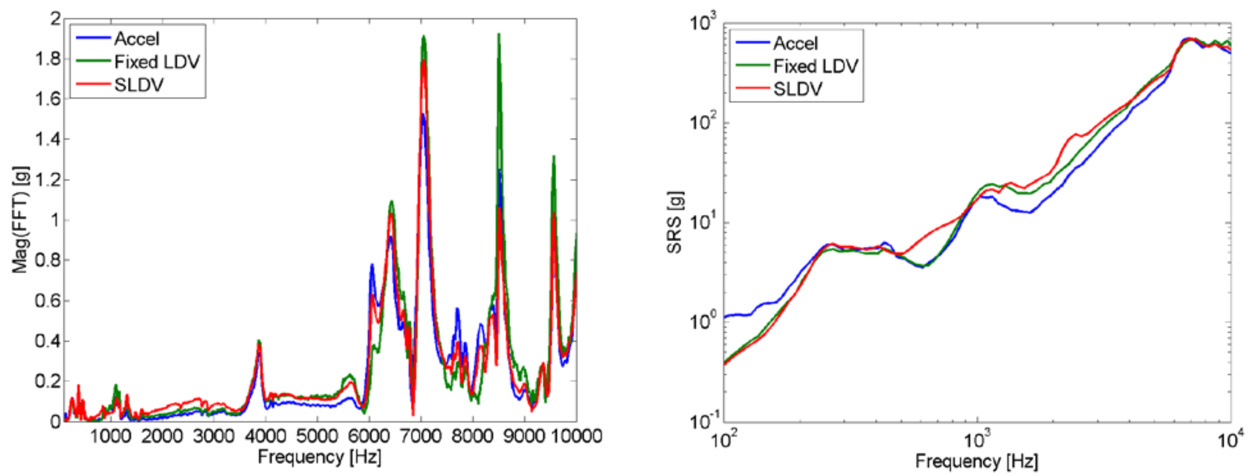

Figure 4: Frequency domain data of aluminum strike plate: Fast Fourier Transform (left), Shock Response Spectrum (right).

The second test campaign was completed in April 2011 as a collaborative effort between JPL and the United Launch Alliance (ULA). The test article was an "obsolete" electronics box (Figure 5) provided by ULA that was used in a round robin shock test effort (Creaser et al. 2011). The SLDV, accelerometers, and force transducers were used in this test. The SLDV and an accelerometer were positioned to measure approximately the same location of the test article along the shock impulse axis.

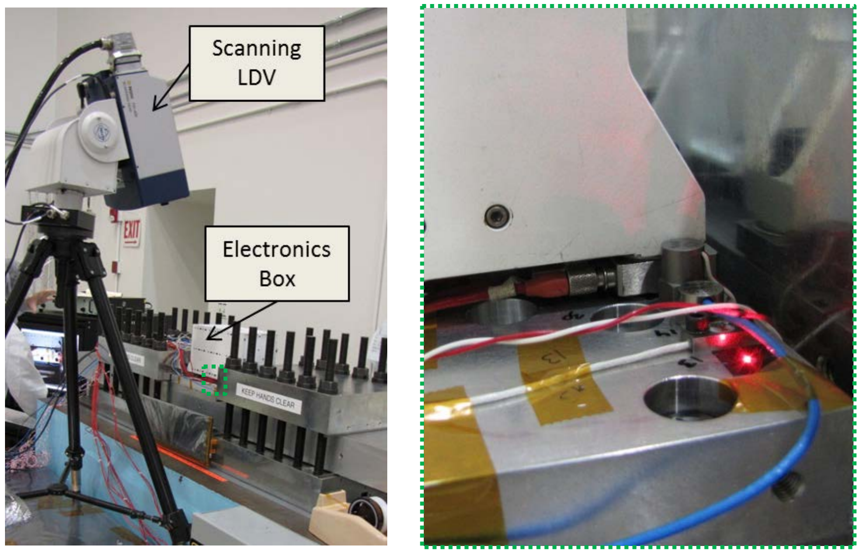

Figure 5: Shock simulation tests on electronics box using a Laser Doppler Vibrometer and accelerometer.

Several runs were completed with 100 psi and 150 psi gas pressure levels. Results of these runs, including time history, FFT, and SRS plots, are provided in Figure 6 through Figure 9. These plots show again good correlation between the accelerometer and SLDV sensors. The SRS plots (Figure 7 and Figure 9, right) show a higher accelerometer measurement compared to the SLDV throughout the frequency domain. A possible source for these differences is the angled laser beam and some beam reflections off of the accelerometer (Figure 5), which may have impacted the SLDV measurements. Due to the setup required for the SLDV, the laser beam was not perfectly orthogonal to the measured surface.

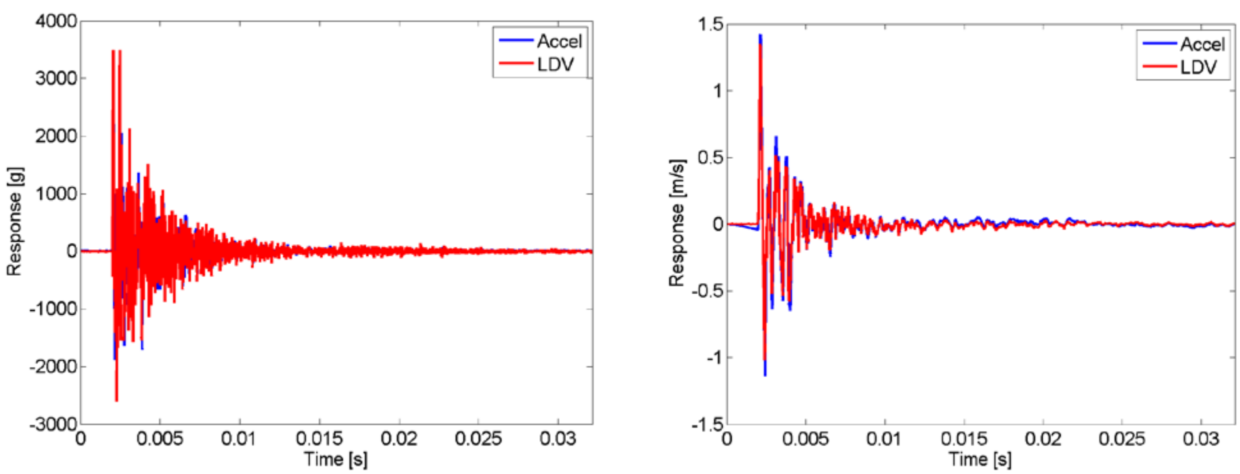

Figure 6: Time history data of electronics box (100 psi input): acceleration units (left), velocity units (right).

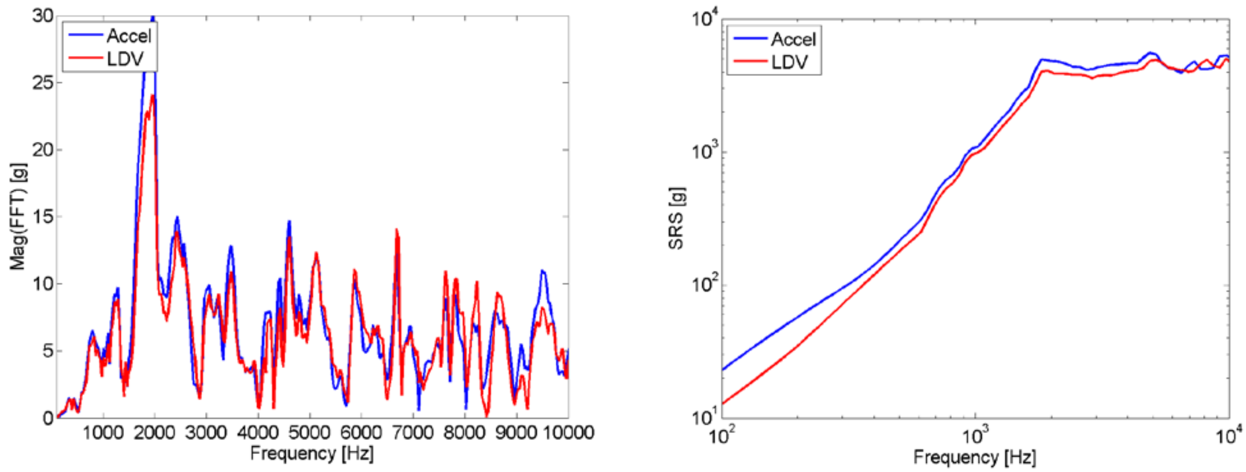

Figure 7: Frequency domain data of electronics box (100 psi input): Fast Fourier Transform (left), Shock Response Spectrum (right).

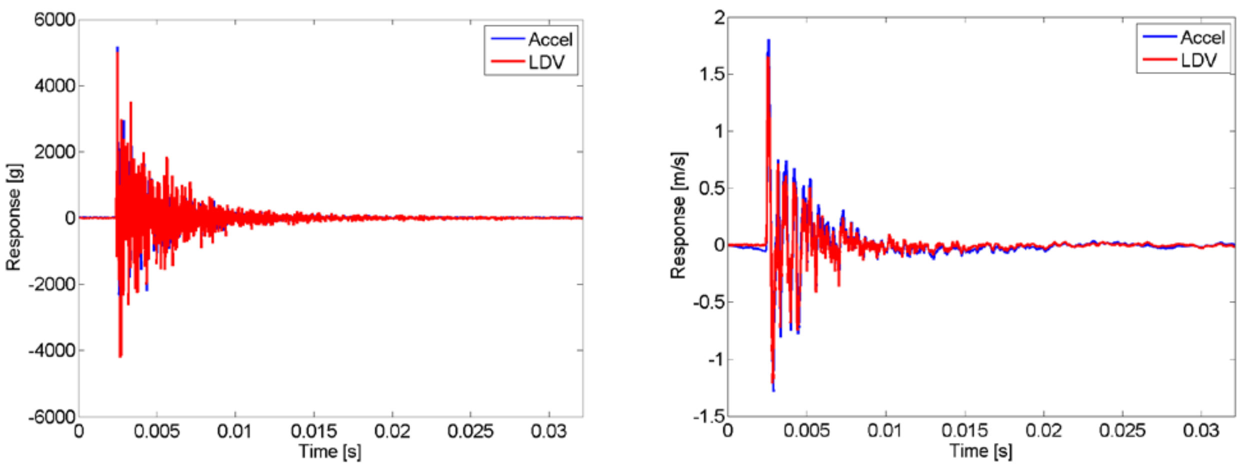

Figure 8: Time history data of electronics box (150 psi input): acceleration units (left), velocity units (right).

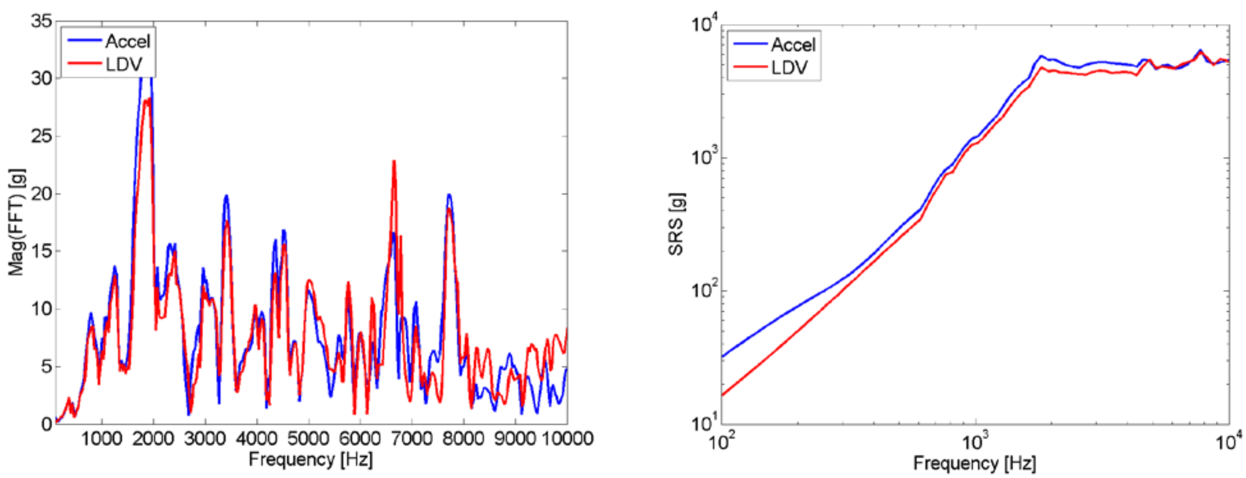

Figure 9: Frequency domain data of electronics box (150 psi input): Fast Fourier Transform (left), Shock Response Spectrum (right).

From the two test campaigns, it is evident that the measured responses from the accelerometer and LDVs are comparable. Differences in the results between the two test campaigns can be attributed to variances in the test article, test setup, SLDV positioning, and load levels. As it is assumed that the stud mounted accelerometers are interfering with the shock wave and distorting the measured responses, it is not definitive at this time which sensor provides a more accurate measurement of the shock environment.

CONCLUSIONS

Shock simulation tests have been completed at the Jet Propulsion Laboratory to explore the feasibility of using Laser Doppler Vibrometers as alternatives to the more commonly used accelerometers. Stud mounted accelerometers can interfere with the shock waves and distort the acquired signature. Other concerns with using accelerometers in shock testing include high frequency limitations, mounting restrictions for sensitive or inaccessible surfaces, and mass-loading affects that become increasingly problematic with smaller instruments and devices. Laser Doppler Vibrometers offer unique opportunities to shock testing as they are non-intrusive optical sensors.

The results from the shock simulation tests show a good correlation between the accelerometer and Laser Doppler Vibrometer measurements. In the electronics box test, the accelerometer responses were higher than the Laser Doppler Vibrometer responses. In the aluminum strike plate test, however, the accelerometer responses were higher in low frequency ranges where the Laser Doppler Vibrometer responses were higher above 500 Hz. Differences in the setup, test article, and load levels may be the cause for these discrepancies. Future efforts should include tests of a single structure in all three axes for a number of shock levels.

The disadvantages found with using Laser Doppler Vibrometers include portability, potential setup difficulties, and measurement limitations if the surface is not optically visible. Further work is needed to prove the benefits and practicality of using Laser Doppler Vibrometers in environmental testing to qualify flight hardware, but the outlook is promising.

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BIOGRAPHIES

Dr. Shannon M. Statham is a Systems Integration and Test Engineer at the Jet Propulsion Laboratory. She received her Ph.D. in Aerospace Engineering from the Georgia Institute of Technology in 2011 with a focus on structural health monitoring, dynamic testing, and fault diagnostics. She is also an Amelia Earhart Fellow. Shannon.Statham@jpl.nasa.gov

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