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Application of fiber Bragg grating sensors and a fiber optic laser Doppler vibrometer for hypervelocity impacts

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Abstract. Hypervelocity impacts occur frequently in space due to dust that occurs naturally from comets or other space debris often called meteoroids; other debris is man-made and can have disastrous effects on spacecraft. Even though the particle may have a very small mass its momentum can be extremely high and destroy space craft. It is therefore vitally important to simulate the effects of hypervelocity impacts on vulnerable areas of satellites and space stations. A two stage light gas gun was previously developed for this purpose. In this paper we briefly describe two fiber optic based impact measurement systems that were tested at the light gas gun facility at the University of Kent to establish that they could provide data that could not be obtained by any other technique.

1. Introduction

To simulate impacts in space we used the 'light gas gun' (LGG) at the University of Kent, which can 'fire' small particles at velocities ranging from 1 km/s to 8.4 km/s. The LGG is used extensively for research in aerospace to analyse the effects of high speed impacts on materials. Ideally the measurement should be made close to the centre of the impact to minimize corruption of the data from edge effects and survive the impact. Typically the sensor used is conventional polyvinylidene fluoride (PVDF) which has high sensitivity combined with high survivability and low cost. A problem with the PVDF is that it has to be mounted at the edge of the target rather than its centre which will result in errors in the impact measurements.

Fig 1 The Kent [1,2] two stage LGG fires small projectiles (1 micron to 1 mm size) at speeds from 1 km/s to 8.6 km/s. The speed is measured in each shot to better than 1% accuracy and the target chamber evacuated to typically 0.5 mbar during a shot. Targets can be powered and instrumented during a shot permitting real time read-out of any impact sensors on the target..

2. Fiber Bragg Grating Sensors (FBG)

In order to make measurements with an FBG it has to be attached under strain to the target causing a very small error. The targets evaluated for impact damage were aluminium or composite carbon plates, 1.6 mm and 1.5 mm thick respectively; the plates were 15 by 15 cm with mounting holes at each corner. The plates were mounted on a free standing rigid jig designed for mounting in the LGG. The jig allowed the FBG to be either surface or orthogonally mounted to the plate. For surface mounting the FBG was attached at ~1.5 cm from the centre of the plate along a line parallel to the plate edge at a distance of 1.75 cm from the plate centre. In the mounting process the FBG was linearly strained to ensure bidirectional strain response (SUFBG). To enable orthogonal mounting a small hole was drilled through the plate ~2.5 cm from the plate centre along a line parallel to the plate edge. Part of the input fiber just before the FBG was attached to a miniature 3D translation stage. The fiber on the other side of the FBG was passed through the small hole on the surface of the plate and attached to a small fitting which prevented the fiber from breaking,. The FBG was then statically strained at ~ 2millistrain again ensuring bidirectional strain response (OTFBG)

3. Interrogation

The stress induced change in the mean reflecting wavelength of the FBG was converted to the time domain where the data is presented in a waterfall [3] format. This method has the ability to measure high strain at high frequencies. In another approach the dynamic variation of the spectral profile of the FBG could be determined during an impact[4]. For the measurements reported here the effective scanning rate was 10 kHz, the number of sequences in the water fall was 500 and the time between sequences 200μs.

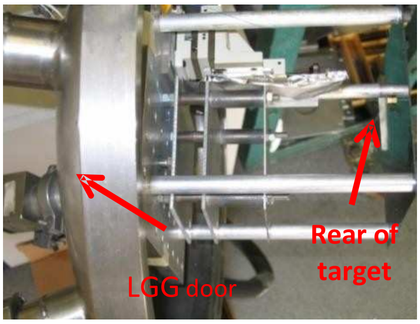


Fig 2 Target area for OTFBG

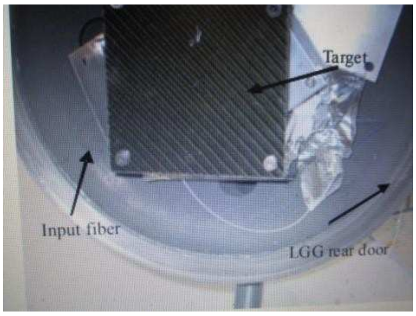


Fig 3 SUFBG mounted on rear of target

Results data shown in Fig 4(a)&(b) is for an OTFBG; no meaningful data was recovered with SUFBG

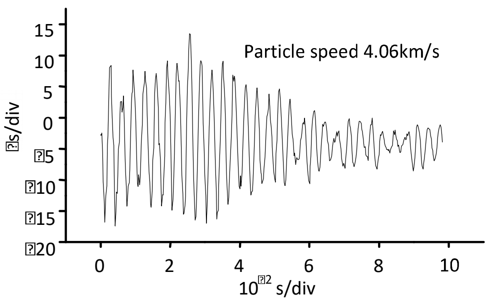


Fig 4(a) Variation of Δt (strain) as a function of time after being impacted at 4.06 km/s

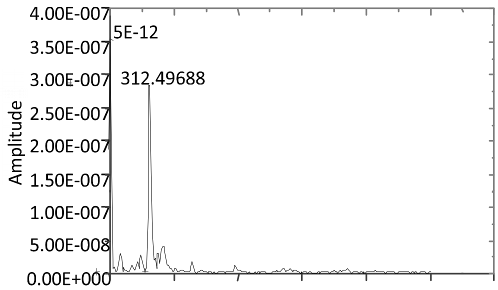


Fig 4(b) FFT of impact at 4.06Km/s

4. Multichannel Fiber Laser Doppler Vibrometer (MFLDV)

In order to overcome the problems using FBG sensors a 4 channel MFLDV[5] was researched and developed.

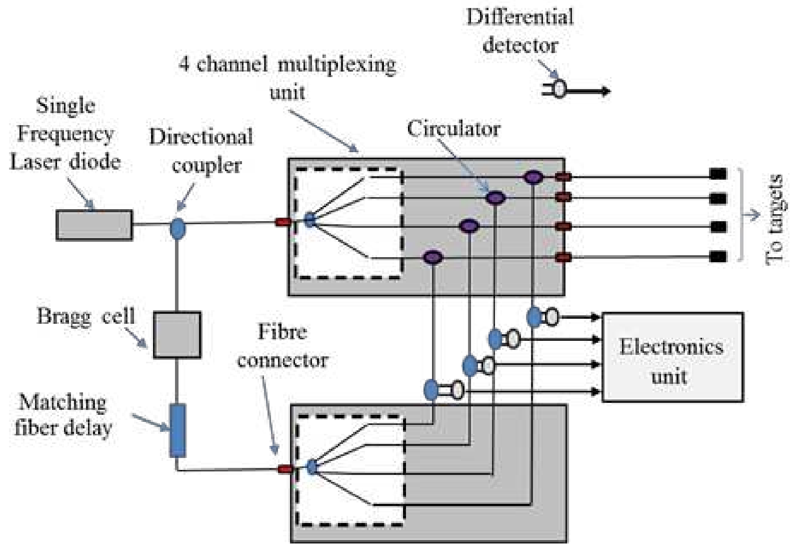


Fig 5 The complete MFLDV is reported in detail in [5]. It contains two 1 to 4 channel multiplexing units. Light from a single frequency 1500 laser diode is transferred to two paths by a 3dB directional coupler. The light on one of the paths propagates to the targets via 4 circulators and hence to 4 variable focus autocollimators where the back reflected signals are transferred to the inputs of four 3dB couplers. The light propagating along the second path is frequency shifted by ~40 MHz with an acousto-optic modulator. It then propagates through a matching fiber delay where it splits into 4 channels and is transferred to the other inputs of the 3dB couplers. Here it mixes with light back-reflected from the targets and is detected by photodiodes in the electronics unit. The phase is preserved by the topology. The Bragg cell frequency of 40 MHz was down shifted to 5 MHz to match the 4 channel 10 MHz digital processor used.

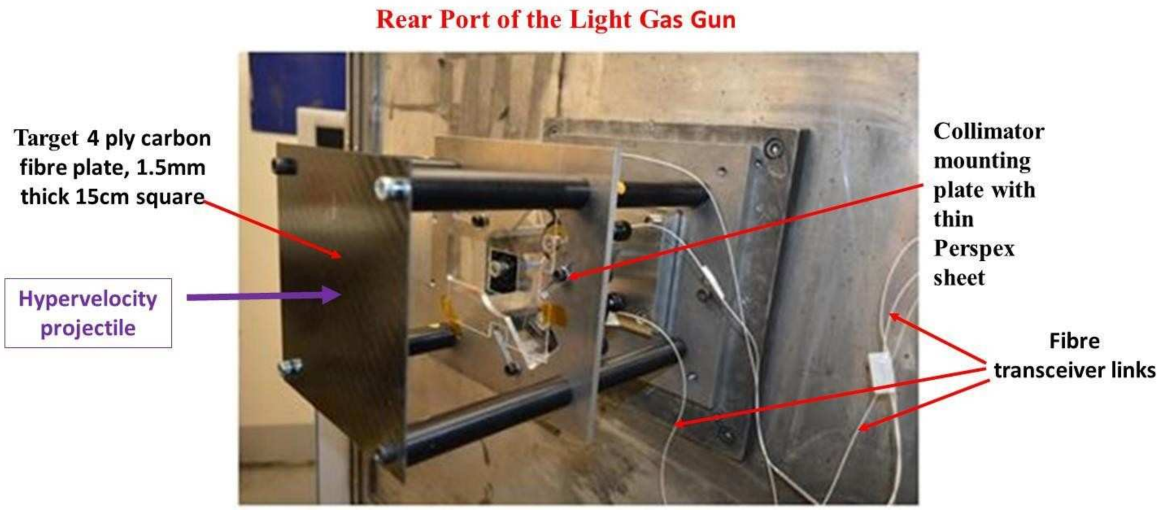
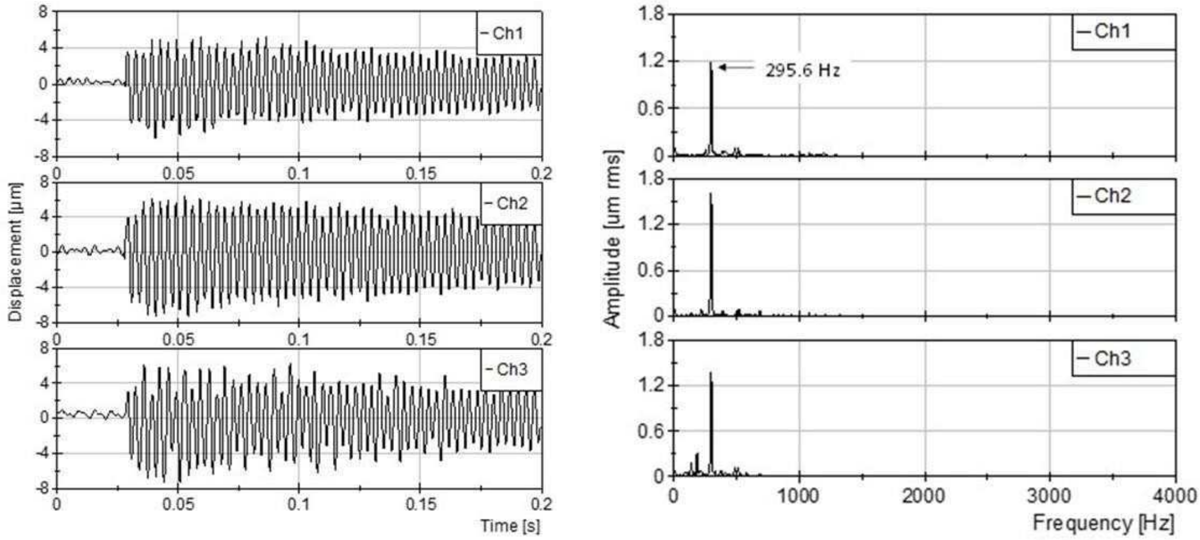


Fig 6 shows the opened rear port door of the LGG with the fully instrumented target mount. The fiber probes (only 3 deployed) shown in Fig 5 were mounted behind the target. Small discs of reflective tape were placed manually at selected locations on the rear side of the target. The collimators were focussed on the reflective discs; the distance between the collimators and rear of the target was about 15 cms.

5. Results

Fig 7, Shows hypervelocity impacts caused by a steel ball-bearing 1mm in diameter, 0.004g mass, velocity, 2.11 km/s, indicating how well the MFLDV performed.



LHS is the raw data from Ch1 to Ch3, RHS shows the FFT corresponding to each channel

The fundamental frequency is 295.6 Hz. Small peaks indicate complex low level movement of the plate. A second shot at a velocity 4.21 km/s shows similar results except data was only gathered from 2 channels as the debris from the impact broke one of the fiber leads in the LGG.

6. Discussion

FBGs have been successfully exploited in many difficult environments, but as shown above the requirement for it to be attached to the target affects the vibrational spectrum of the target. Another problem is the low resolution compared with interferometric sensors. Multiplexing is one of the main attributions of FBGs as it increases the sensor density, but in the case of an impact it would produce significant errors due to the extra loading of the target. From the data shown above it is clear that for the hypervelocity impacts the MFLDV is superior with nanometer resolution and noncontact sensing.

7. References

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