DYNAMIC LOAD ANALYSIS OF EXPLOSION IN INHOMOGENEOUS HYDROGEN-AIR

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ABSTRACT

This paper presents results from experiments on gas explosions in inhomogeneous hydrogen-air mixtures. The experimental channel is 3 m with a cross section of 100 mm by 100 mm and a 0.25 mm ID nozzle for hydrogen release into the channel. The channel is open in one end. Spectral analysis of the pressure in the channel is used to determine dynamic load factors for SDOF structures. The explosion pressures in the channel will fluctuate with several frequencies or modes and a theoretical high DLF is seen when the pressure frequencies and eigen frequencies of the structure matches.

1.0 INTRODUCTION

Hydrogen is now introduced as a zero emission energy carrier in the road, rail, and sea transport sector. The successful introduction of hydrogen in these new sectors will require high safety standards. Intended or accidental releases of hydrogen may cause fires and explosions. Such events are a concern and have to be taken into consideration when new technology is introduced. To understand the consequences of gas explosions a large number of explosion tests with hydrogen and other fuels have been carried out the last decades. In addition, numerical codes for dispersion, fires, explosion and the structural response have been developed for scientific and risk analysis purposes.

Most of the experiments on gas explosions are done with the homogeneous gas mixtures. Only a few experiments are done within an inhomogeneous gas cloud. How realistic homogeneous clouds are regarding accidental releases is still an open question. In simulations of structural response from gas explosions, the standard way of describing the load is using maximum explosion pressure and duration of the first positive peak. However, when we have an explosion in channels, tunnels or confinements with long length over width ratios, the explosion pressure may exhibit strong oscillations over several periods for relatively long times.

The aim of this paper is to study structural response using experimental pressure data from explosions in inhomogeneous clouds with multiple oscillations as the load in a single degree of freedom model. Since various equipment or piping inside, for instance, tunnels can have different values of fundamental frequencies (stiffness and mass) this study focusses on the general behaviour. The results will be presented as dynamic load factor as a function of frequency based on the experimental data.

The paper contains first the brief description of the structural response model that we used followed up by a description of the experimental setup for the gas explosion test. The results in form of high-speed film images, pressure recorders, spectrograms and dynamic load factor (DFL) calculation are then given and discussed.

2.0 SINGLE DEGREE OF FREEDOM MODEL AND DYNAMIC LOAD FACTOR

When a structure is subjected to an explosive load the response or motion of the object will depend on several factors among them; the mass of the structure, the eigen frequency of the structure, the damping and of course the pressure load. A simple way of modelling the response is to apply a single degree of freedom model (SDOF). In such analysis, we treat the structure as a mass-spring system as illustrated in Figure 1. When this system is subjected to a time-dependent force, $F(\mathrm{t})$, the position or displacement, $x(\mathrm{t})$, of the mass, m, can be found from Newton's second law. If the load is a static load, $F = \max(F(\mathrm{t}))$, we will have a static displacement, x_{Static}. When we have a dynamic load the displacement, x (t), will be a function of time. The maximum displacement, x_{max}, is a characteristic of the dynamic response. The ratio between the maximum displacement and the static displacement is known as the dynamic load factor (DLF = x_{Max}/x_{Static}). In the present analysis, we will use the dynamic load factor to characterise the response for a simple single degree of freedom model (SDOF) subjected to a load given by our experimental pressure.

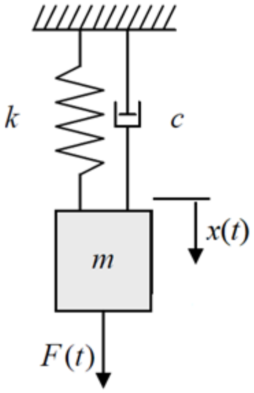

Figure 1: Single degree of freedom model (SDOF), where k is spring stiffness, c is damping factor, m is the mass of the system and F(t) is the explosion load.

Discussions of the single degree of freedom model (SDOF) for a structural response can be found in reference [1- 4]. The differential equation to be solved is $F(t) = mx'' + cx' + kx$ where m is the mass, c is the damping factor and k is the spring constant. The system has a critical damping factor $c_{cr} = (km)^{1/2}$ and a fundamental frequency $f = (1/2\pi)\ (k/m)^{1/2}$. According to [3]; "*Biggs suggests that damping in most actual structural systems does not generally exceed 10 percent of critical*".

3.0 EXPERIMENTAL SET-UP

The test channel was 3 m long, 0.1 m wide and 0.1 m high, which was open at one end and closed at the other end. The test channel is shown in Figure 2 and 3. The side walls of the channel were made of transparent polycarbonate walls. The experiment was carried out by releasing hydrogen from the cylinder through a 0.25 and 0.5 mm diameter nozzle into the channel. The injection point was either at the closed end wall or in the middle of the channel. The flow rate was controlled by the back pressure of a regulator valve. The back pressure varied from about 1.2 to 8.0 MPa corresponding to hydrogen flow of 15 to 80 liter/min. A continuous ignition source, i.e. high voltage spark, was mounted at the upper wall of the channel. In the test program, five different ignition locations (Ign#1 to Ign#5) was used. The location of the ignition was 0.5 m, 1 m, 1.5 m, 2 m and 2.5 m from the closed end of the channel. The ignition source was switched on and off in a series of short continuous pulses. Four Kistler 7001 pressure transducers were used to measure the explosion pressures with a sampling rate of 100,000 samples/s. The position of the four pressure transducers is shown Figure 3 as P#1 to P#4 in. we used a Photron Ultima APX-RS (black and white) high-speed camera to film the experiment. The frame rate was 1500 fps or 2000 fps and resolution of 1024 x 64 pixels.

Figure 2: Picture of the experimental rig.

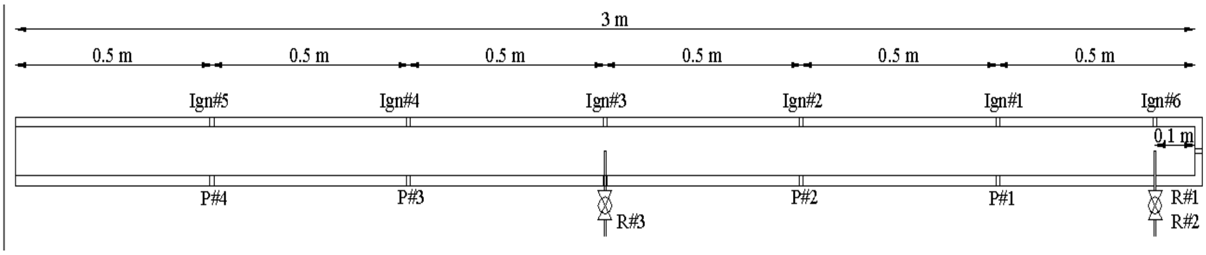

Figure 3: Schematic diagram showing the ignition locations (Ign #1-Ign #5), pressure transducers (P#1-P#4) and hydrogen inlet locations(R#1-R#3).

4.0 EXPERIMENTAL RESULTS

Since the objective of this paper is to analyse the structural response, only a limit number of experiments will be included here. We will not discuss dispersion, flame acceleration etc.

We have chosen three experiments that are typical for this experimental series. The first experiment, Test #30 have a short ignition distance and the gas cloud in the upper part of the channels is near stoichiometric. In Test #150 the cloud is slightly rich and the distance from the jet release to the ignition point is 2 m. The cloud in the third test, Test #67, is very rich and the ignition is 2.5 metre from the closed end of the tube

The experimental results are presented in form of three types of figures, shown in figures 4, 5 and 6. The first type is shown in Figure 4 and is an image prepared from the high-speed video and the pressure records. At the upper part of the figure an image from the high-speed video is showing the flame front. In the middle part, four pressure records are presented as a pressure-time diagram. The time axis is downward and the scaling is presented in the middle of the figure. The time scale is either 30 milliseconds (Test #67) or 100 milliseconds (Tests #30 and #150). The pressure scale in the horizontal direction is 25 or 10 kPa. The pressure records are placed relative to their position in the channel in the high speed image so that zero pressure in the records are placed at the position of the pressure transducers. The whole pressure record is plotted as a white line. The red point on the curve marks the pressure and time of the video image. Spectrograms for each of the pressure records showing the maximum power frequency is in the bottom of the image, below the pressure curves,

The second type of figure is shown in Figure 5. The upper subplot is a spectrogram showing frequency and power frequency vs time. The spectrogram is made from the standard MATLAB function which returns the short-time Fourier transform of the pressure record P#1. The lower subplot shows the pressure record P#1.

Figure 6 shows the third type of figure and is the main results from of analysis. It shows four graphs of the calculated dynamic load factor (DLF) as a function of the frequency. The legend of the upper right corner of the figure shows the dimensionless damping factor, c. The dimensionless spring constant, k, in these calculations are set to unity, and gives the values for the other parameters. The blue curve is the undamped system (i.e. $c = 0$). The critical damping factor, c_{cr}, is also a function of the mass and the frequency. As discussed in section 2 the damping factor will normally be between 0 and 10% of the critical damping factor. The curve for 10% critical damping factor is the violet coloured curve. We have also included two curves with a constant damping factor of 10^{-3} and the other 10^{-4}.

4.1 Test #30 - Short Ignition Distance (Ign#1) and Near-Stoichiometric

In Test #30 the distance between the spark and jet nozzle it was 0.4 m. The high-speed film showed that the flame propagated directly from the spark and into the turbulent jet without creating pressure oscillations in the channel. The first peak was 23 kPa followed by a second pressure peak at the same level. At the time of the second peak, most of the fuel was burned and the pressure records showed damped oscillations. It took approximately 13 cycles before pressure peak was roughly 10% of the maximum pressure as seen in Figure 4.

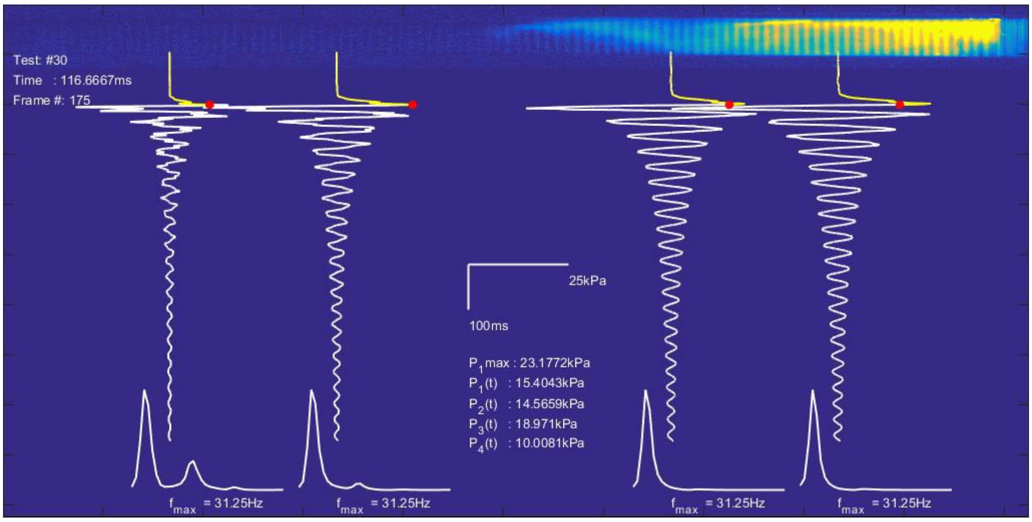

Figure 4: Frame from high speed movie of Test #30 with the explosion pressure below and power spectrum at the bottom.

The results from the spectral analysis is shown in Figure 5. One frequency of 30 Hz is dominating the spectre. The 30 Hz frequency corresponds to the fundamental frequency (i.e. first harmonic) of the channel for the speed of sound for air at the initial temperature. This should be expected since only a small part of the channel was filled with hydrogen-air at the time of ignition in test #30. We also see some higher frequencies around 150 and 250 Hz.

The dynamic load factor (DLF) for the no damping case has a spike of 12 at 30 Hz. For the 10%, critical damping constant gives a DLF of 3.

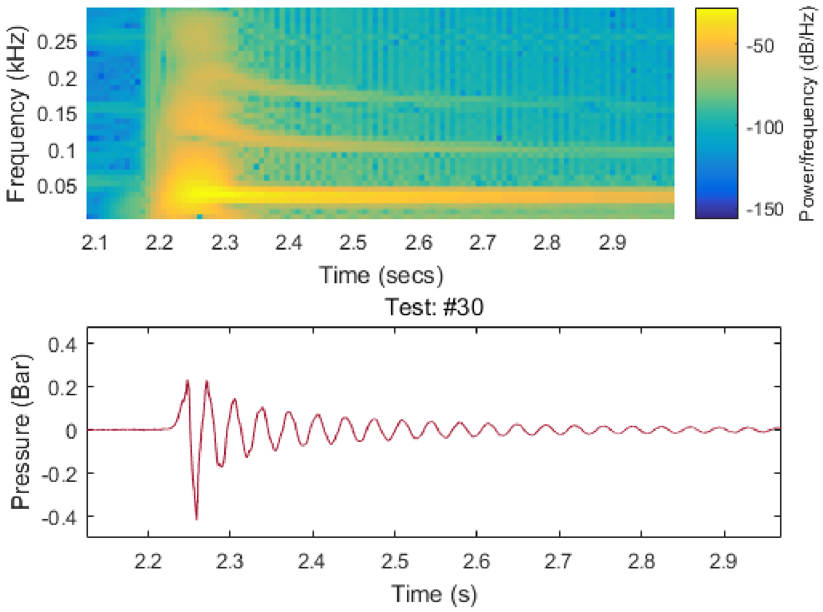

Figure 5: Power spectrum as a function of time on top and pressure records below, Test #30.

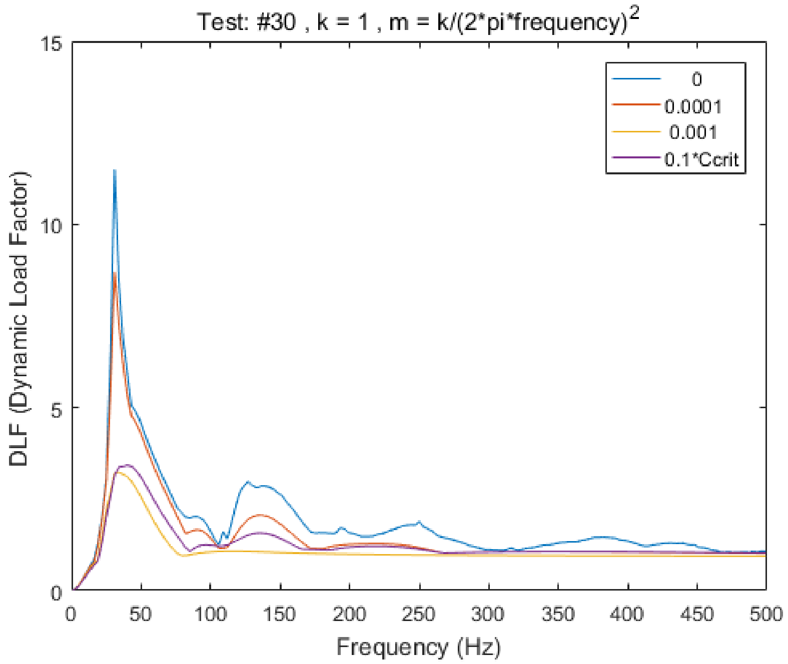

Figure 6: Calculated DLF from results of Test #30 with damping factors 0 (undamped), 0.001, 0.0001 and 10% of critical damping factor.

4.2 Test #150 – Medium Ignition Distance (Ign#4) and Slightly Rich

In Test 150 the ignition was placed 2 m from the closed wall. The hydrogen-air mixture in the gas cloud was slightly rich. The maximum explosion pressure was only 6.2 kPa and the pressure record showed a different behaviour than in the previous test. In this test, the oscillations starts at an early phase of the flame propagation and we see several periods of pressure oscillations as the flame propagates into the channel. In Figure 7 we see that the oscillation frequency on pressure transducers #1 and #2 peaks at 54 Hz (reactants) and for transducers #3 and #4 the peak is at 148 Hz (products).

In the first 200 ms of flame propagation after the first pressure peak, the pressure oscillations are slightly damped. This is most clearly seen on pressure transducer #3, when the flame reaches 1 m from the closed end the pressure oscillations are strongly amplified. This is a well-known phenomenon in homogeneous pre-mixed fuel-air when the flame propagates in tubes with an open and closed end and the ignition is at the open end. A classic experiment of this type can be found in Putnan [5]. He showed that strong oscillations in pressure are observed when the flame propagated to about 2/3 of the tube. In Figure 8 the flame has reached about 2/3 of the 3 m channel, we see the amplification of the pressure oscillations, and the peak frequencies have shifted to 70 Hz.

From the spectrogram, in Figure 9 we see that the peak frequency is increasing more or less linearly with time from 50 to 70 Hz the first 200 ms after ignition. This can be explained by increasing speed of sound in the channel as the flame burns through the channel and fills it up with hot combustion products. The higher frequencies show the same behaviour. It is also interesting to observe that after t > 7 s, when the fuel is consumed, the fundamental frequency settles rapidly to 40 Hz.

The DLF curve in Figure 10 for the undamped case (i.e. c = 0) shows two distinct peaks; one at 50 Hz and one at 150 Hz. The peak values are about 12 for both. For the 10%, critical damping constant a DLF of 5 is observed. Test #150 has more variations in frequencies than Test #30, which results in a wider spectre of high DFLs over the frequency range.

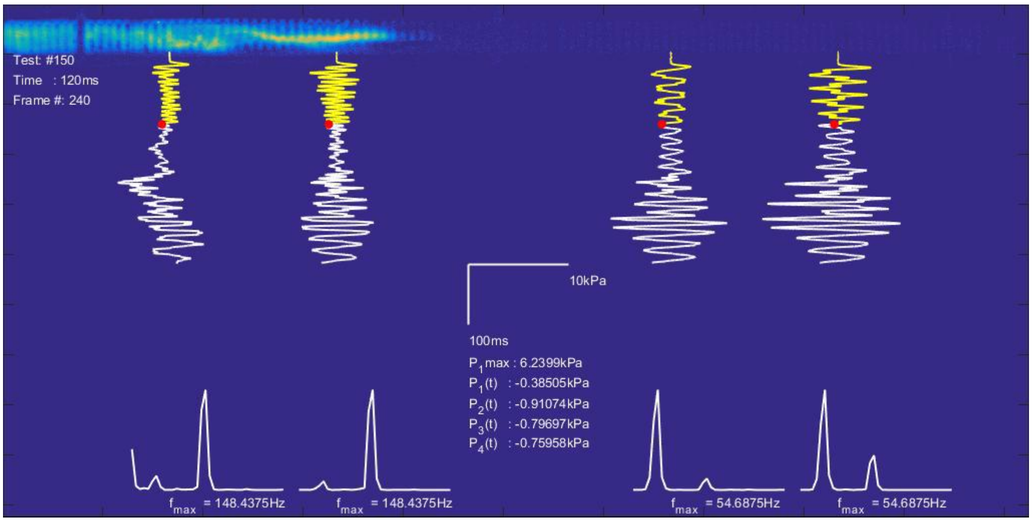

Figure 7: Frame from high speed movie of Test #150 with the explosion pressure below and power spectrum at the bottom.

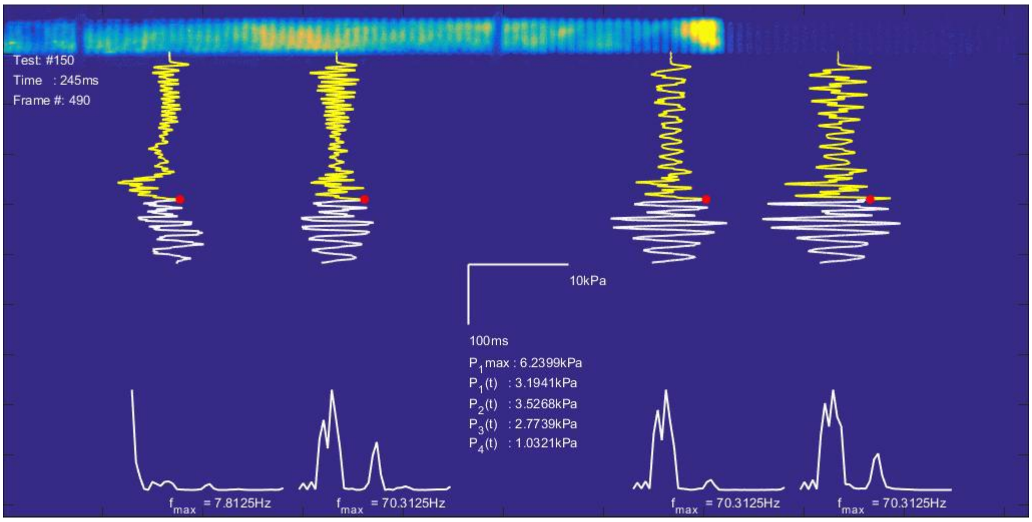

Figure 8: Frame from high speed movie of Test #150 with the explosion pressure below and power spectrum at the bottom.

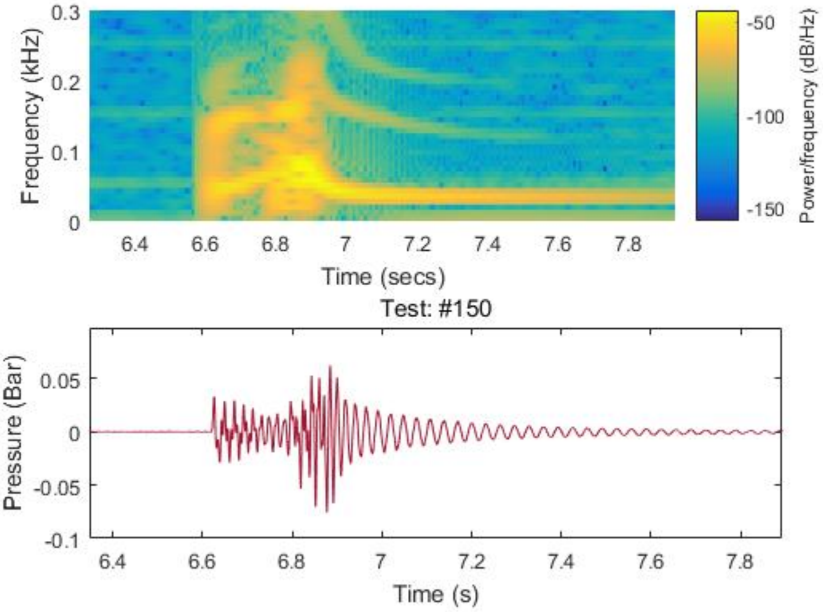

Figure 9: Power spectrum as a function of time on top and pressure records below, Test #150.

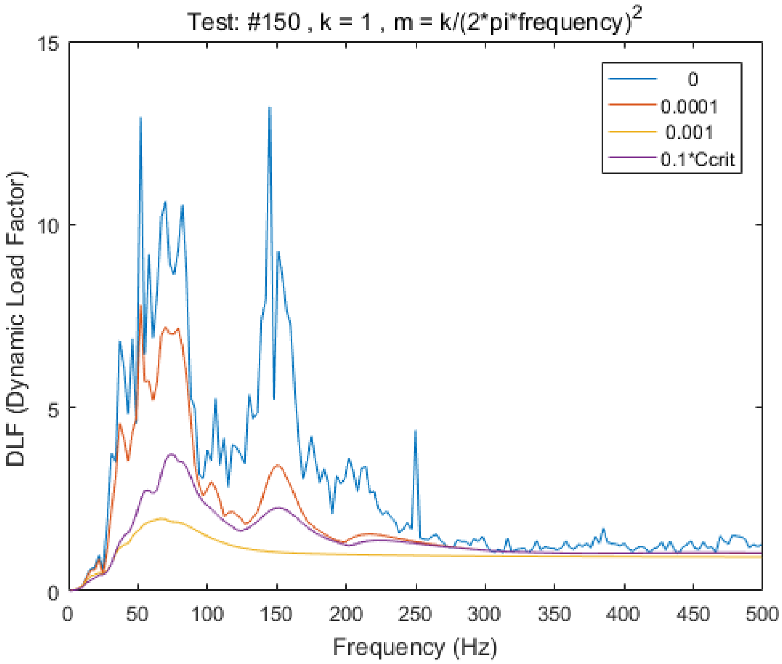

Figure 10: Calculated DLF from results of Test #150 with damping factors 0 (undamped), 0.001, 0.0001 and 10% of critical damping factor.

4.3 Test #67 - Long Ignition Distance (Ign#5) and Very Rich

In Test #67 the gas cloud was very rich with an estimated average concentration of 60 to 70 % H_2. The ignition point was 2.5 metre from the closed wall. The peak pressure in this experiment was 41 kPa. The high-speed film shows rapid flame propagation through the channel. The flame fills not only the upper part of the channel but whole cross section. Also in this test, a localised explosion occurred when the flame has reached about to 2/3 of the channel length.

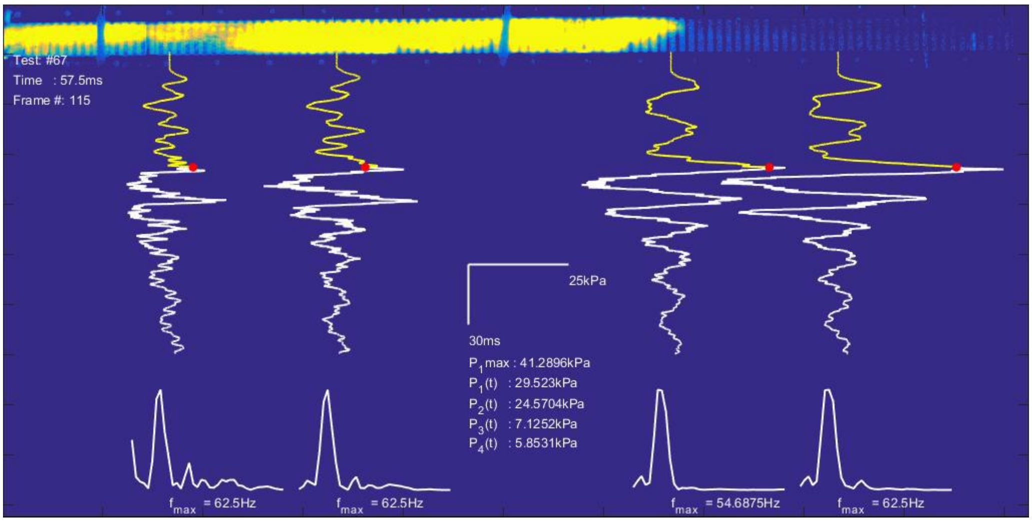

Figure 11: Frame from high speed movie of Test #67 with the explosion pressure below and power spectrum at the bottom.

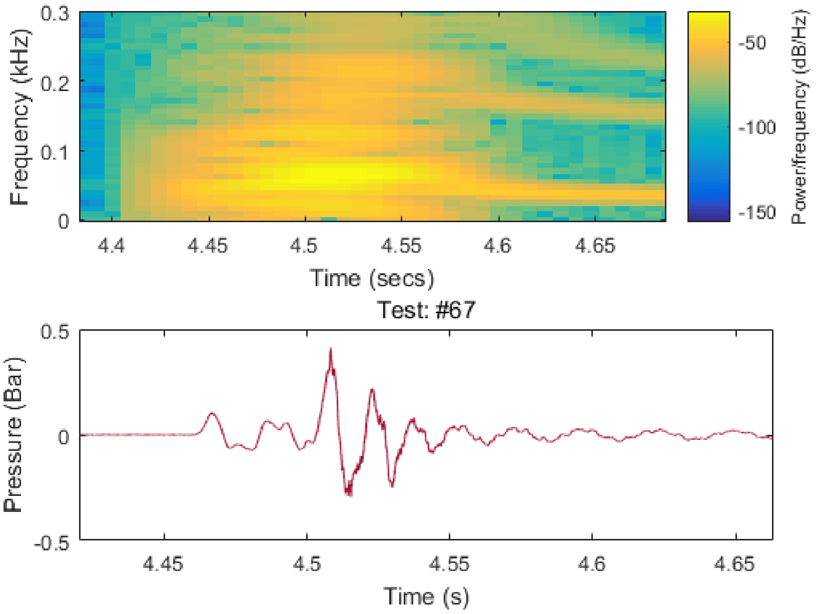

Figure 12: Power spectrum as a function of time on top and pressure records below, Test #150.

Figure 12 shows the pressure and the spectrogram for P#1. The pressure record shows a relatively high peak pressure of 41 kPa, but the damping of the peak pressure takes only 3 cycles before the amplitude is reduced by a factor of 10. This rapid damping of the pressure results in a relatively low dynamic load factor (DLF) as shown in Figure 13. The maximum DLF is 5 for the undamped case.

To explain the relatively low DLF in Test #67 we have plotted the pressure records for all the three tests in Figure 14. We have used the time at maximum pressure as a time reference (t = 0). The upper subplot shows Test #67 and #150. The main difference between these two pressure records is that Test #67 has two high amplitude pressure peaks while #150 shows a more smooth oscillating pressure curve. After 3 to 4 cycles both curves are very similar. The static displacement distance x_{static} is given by the maximum pressure. Since the maximum pressure peak in test #67 is relatively high the DLF will be relatively small for test #67.

The lower subplot shows Tests #67 and #30. Both these experiments has had a strong pressure peak but the oscillations in Test #30 are not dampened as quickly as in Test #67. In Test #67 the gas in the channel is light gas in form of hot combustion products or high fraction of hydrogen while in Test #30 the gas is mostly cold air with a higher density. Therefore, it is more mass that is oscillating in Test #30 than in Test #67. The difference in viscosity might also have an influence on the damping.

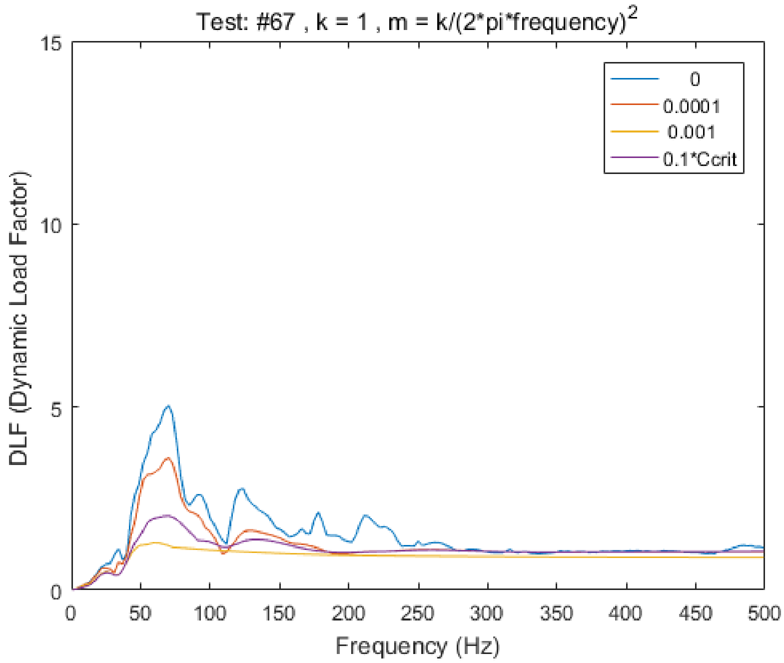

Figure 13: Calculated DLF from results of Test #150 with damping factors 0 (undamped), 0.001, 0.0001 and 10% of critical damping factor.

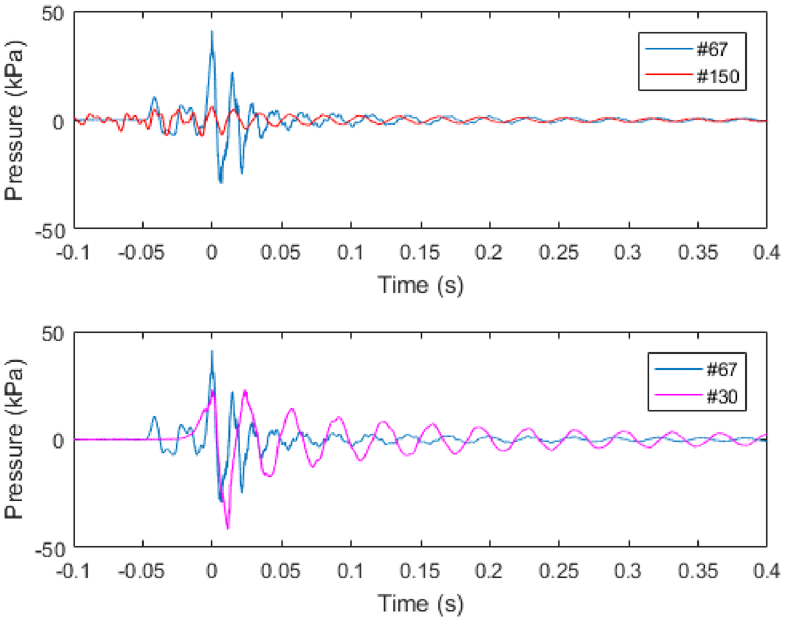

Figure 14: Pressure histories for Tests #67 and #150 (top) and Tests #67 and #30 (bottom).

5.0 CONCLUSIONS

The present gas explosion tests in a 3 m channels with inhomogeneous hydrogen-air showed strong pressure oscillations with several cycles. To estimate the structural response from explosions it is common to use only the first cycle and/or the highest-pressure cycles as the load. This approach will typically result in a dynamic load factor of about 2 or lower.

When we use pressure load with multiple cycles from our experiments as the load in structural response calculations we find that for certain frequencies, dynamic load factors can be up to 12 for the undamped case.

We conclude from our experiments and calculations of DLF that the structural response from gas explosions in tunnels, channels or compartments with long length to width ratio should consider multiple cycle oscillation. The structural response of equipment inside these kinds of structures can be much more severe when considering several cycles of pressure oscillations. When the frequencies in the pressure oscillations are close to the fundamental frequencies of the structures or equipment, the DLF can be much higher than 2.

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