Misalignment effects using blast pencil probes

Stian Skriudalen, Arild Skjold, Bjørn Hugsted,
Jan Arild Teland and Morten Huseby

FFI Forsvarets
forskningsinstitutt

Misalignment effects using blast pencil probes

Stian Skriudalen, Arild Skjold, Bjørn Hugsted, Jan Arild Teland and Morten Huseby

Keywords

Trykksensorer

Sjokk

Skjevinnstillinger

PCB 137

Approved by

Eirik Svinsås	Project Manager
Jon Skjervold	Director

Summary

This report investigates the use of blast pencil probes and the effect on the pressure-time history when having a non-optimized alignment of the pressure gauges, the so-called misalignment effect. This may be of special importance when we are dealing with a non-static blast source, several blast sources or with a complex blast environment having several reflected waves impinging the blast sensors.

We first address the pressure-time history changes when having misaligned pencil probes and compare the data to correctly aligned pencil probes. Both simulations and experimental data are considered. Next, we investigate different procedures to compensate for the misalignment effect. Both a filtering procedure and a "by hand"-method are proposed. The pencil probe tested is the PCB 137A23.

The overestimation of peak overpressure, due to misalignment, seems to be slightly dependent on the charge size. However, when looking at the mean value for all charges tested, we see that a misalignment between -10° to +10° results in an error of less than 13 %. The maximum acceptable misalignment angle is of course dependent on the required accuracy.

If the proposed filtering procedure or "by hand"-method is used to correct the peak overpressure, the error of the pencil probe is less than 13 % for smaller charges, while still 15-30 % for larger charges. Whether this observed increase in overestimation is a physical effect or just a stochastic variation in our limited data set is not known, hence no procedure is outlined to compensate for this effect.

Norsk sammendrag

Denne rapporten ser nærmere på trykkmålere av typen PCB137A23 og hvordan en ikke optimal innretting påvirker trykk-tid kurven.

I alle praktiske forsøk der trykk skal måles fra en kilde som ikke er statisk i forkant av og/eller under selve detonasjonen, vil det være en sjanse for at disse trykkmålerne ikke er optimalt innrettet, dvs. at de ikke peker mot selve trykkilden. Arbeidet vil også være relevant for situasjoner der man har flere trykkilder i rommet eller situasjoner der reflekterte trykkbølger treffer sensoren.

Vi ser først på hvordan trykk-tid kurven endrer seg med økende grad av feilinnretting. Dette gjøres ved hjelp av simuleringer og eksperimentelle data. Deretter ser vi på ulike metoder for å kompensere for denne effekten.

De eksperimentelle forsøkene ble utført med C4-ladninger på 100-5000 gram og i en avstand på 5 meter.

Forholdet mellom maksimaltrykket, målt med en sensor som er galt innrettet i forhold til en som er korrekt innrettet, ser ut til å være avhengig av ladningsstørrelsen, som igjen kan innebære en avhengighet av trykkbølgens amplitude og/eller romlig utbredelse (bølgelengden).

Gjennomsnittlig endring i maksimaltrykk for alle ladningene er mindre enn 13 % for en innrettingsvinkel mellom -10° og 10° i forhold til trykkilden.

Manuell korreksjon eller en korreksjon av maksimaltrykket ved hjelp av filtrering gir mindre enn 13 % økning i maksimaltrykket for små ladninger (1 kg eller mindre) mens det fortsatt er 15-30 % økning for de store ladningene. Datagrunnlaget er vurdert for lite til å si noe om dette er en fysisk effekt eller om dette er tilfeldige variasjoner i forsøkene.

Contents

1 Introduction

The blast pencil probe, or tapered pencil gauge, is originally made to measure the side-on (free field) overpressure at locations above ground level [1]. Figure 1.1 shows a pencil probe (PCB 137A23) pointing towards a virtual blast source on top of a steel plate.

Figure 1.1   Blast pencil probe pointing towards a virtual blast source on top of a steel plate.

The characteristics of the pencil probe shown in the figure above is given in Figure 1.2 [2]. The sensing element is mounted flush with the surface and measures 13 mm in diameter. The active diaphragm, located in the centre of the sensing element is 5 mm in diameter. The pencil probe is machined "flat" along the side in order to avoid having the sensor protruding (or countersunk) from an otherwise cylindrical body [1].

1.1 Background

We always want to measure an undistorted blast wave. This is, however, impossible since a measuring device (of some shape and size) needs to be placed into the space where the blast wave is propagating. The pressure wave will be altered when the air flows around this device. It is quite obvious that the smaller the gauge is, the smaller the distortion becomes. It is also (perhaps) quite obvious that the distortion is dependent on the gauge size relative the length scale of the blast wave.

The idea behind the pencil probe is to minimize the distortion as much as possible. The body is thin and (almost) cylindrical and has a tapered tip intended to be pointed towards the blast source.

But still, the blast wave will become distorted, at least for higher frequencies (shorter wavelengths). However, due to the long thin body, the blast wave is more or less reconstituted by the time it arrives the sensing diaphragm.
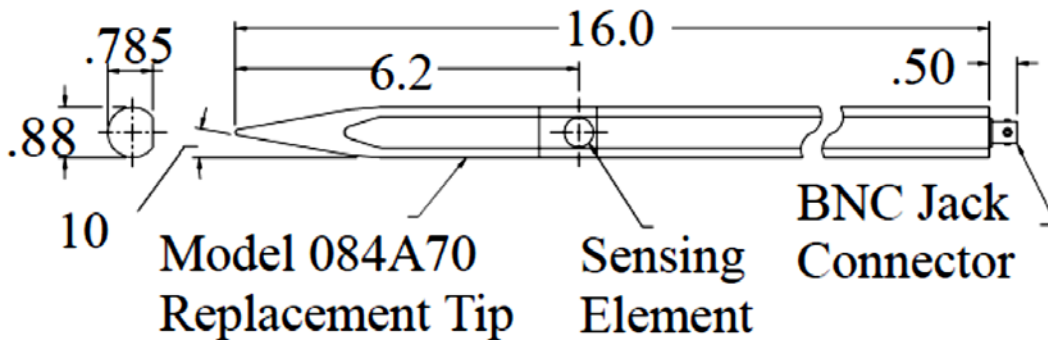

Figure 1.2   Top: Pencil probe (PCB 137A23) with the circular sensing element and amplifier needed for data acquisition. Bottom: Schematic drawing of the pencil probe [2]. Units are given in inches.

So, the correct way to use a pencil probe is therefore to point the tapered probe tip upstream the propagating blast wave. In other words, the blast wave should propagate parallel to the longitudinal axis of the pencil probe. It should only be used in situations where the pressure wave is originating from a single blast source and in situations where there are no reflections from nearby structures [3]. If reflection cannot be avoided, they should at least be distinguishable from the primary (direct) wave, or heavily mitigated by the time they reach the pencil probe, to avoid ambiguity in the measurements.

The alignment of the pencil probe must be done by the measurement team prior to the test, and is often done by sighting along the pencil's longitudinal axis. In cases where the blast source is

statically detonated, this alignment procedure is probably sufficient. However, in cases where the blast source is non-static, the alignment procedure is more complex.

For the sake of illustration, let us consider the following example: In a controlled test, a live fired missile is intercepted by some physical ("hard-kill") countermeasure and detonates. We would like to measure the pressure pulse from this event. First, the expected position of the detonation has to be predicted, towards where the pencil probe should be pointed. The next step is to determine where the actual detonation took place. A typical outcome from a live fire trial is that the actual detonation point deviates from the predicted detonation point. Hence, there is a high risk for the pencil probe to be misaligned. Is it still possible to use the pressure measurement if the pencil probe is misaligned?

Let us break down the current problem into the following questions:

- What happens with the pressure-time history when the pencil probe is not pointing towards the blast source?
- How does the degree of misalignment influence the pressure measurement?
- Is it possible to decide a maximum acceptable misalignment angle?
- Is it possible to compensate for the misalignment effect?

In this report we present both simulations done in ANSYS AUTODYN and experimental work in order to illuminate and answer some of the questions above.

The pencil probe tested is the PCB 137A23 [2]. We believe that the conclusions in this report will be relevant and valid for other pencil probes as well.

1.2 Definition of misalignment

Before we proceed, let us define precisely what we mean by misalignment (Figure 1.3).

When the pencil probe does not point upstream the incoming blast wave, $p(\vec{k}, t)$, there will be an angle between the direction of propagation $(\vec{k})$ of the incoming blast wave and the longitudinal symmetry axis of the pencil probe. This angle is defined as the misalignment angle. We differ between the misalignment in the horizontal and vertical plane, labelled φ and θ respectively. The sensing element is, in our case, assumed mounted vertically.

From now on we will only treat the misalignment angle in the horizontal plane (φ). When we talk about a positive misalignment angle we mean that the sensing element is facing the incoming blast source. Correspondingly, a negative misalignment angle means that the sensing element is on the shadow side.
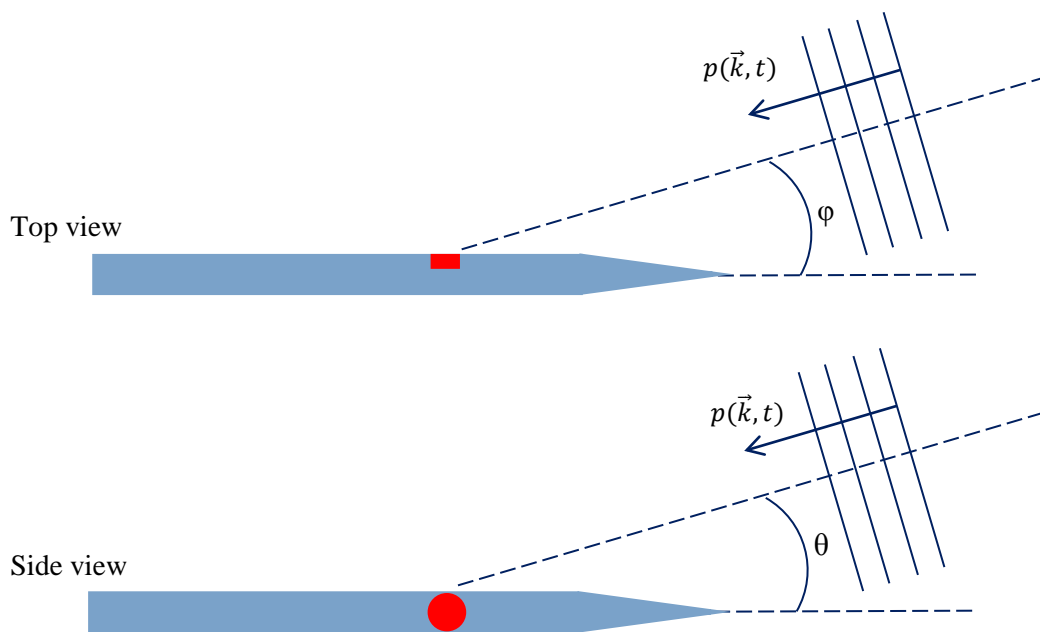
Figure 1.3   Definition of misalignment angles in horizontal plane (φ) and vertical plane (θ). Sensing element is mounted vertically.

1.3   The misalignment effect

The "misalignment effect" is affected by changing three factors:

- Charge size;
- Distance from source to sensor;
- Size of the sensor.

As the blast waves propagate around the sensor, two important relationships are the length scale of the blast wave relative to the size of the sensor and the degree of non-linearity of the blast wave. E.g. a blast wave with a very long wave length, or a pressure gauge with a very small sensor, would eliminate the "misalignment effect".

As a blast wave propagates it will broaden due to geometric attenuation reducing the non-linearity. A larger charge size will result in a lower frequency blast with a longer wave length. As the charge size increases the blast wave length will increase compared to the sensor size. This will tend to make the "misalignment effect" smaller. At the same time non-linearity will increase and as a result we expect a larger "misalignment effect".

2 Simulations

When the pencil probe is misaligned, the projected area of the pencil probe (as seen by the blast wave) becomes larger. The interaction between the pressure wave and the pencil probe is thus expected to increase. When we consider the pressure-time history seen by the sensing element we expect an increase in pressure for positive misalignment angles (i.e. when the diaphragm is facing the blast wave) as the blast overpressure now is partly a reflected pressure and not a pure side-on pressure. For negative misalignment angles on the other hand, our initial expectation is a decrease in the pressure since the sensing element now is facing away from the incoming blast wave. In order to gain more insight into the shock physics around these pencil probes, we make use of numerical simulations.

2.1 Setup

Numerical simulations were performed using ANSYS AUTODYN 14.5. The geometry of the blast pencil was drawn in SolidWorks and imported into AUTODYN using standard settings. It was modelled as rigid and the surrounding area was modelled using an Euler-FCT grid. The pencil probe therefore only acted as a boundary for the gas flow and no waves propagated inside it. To measure the pressure, gauges were placed in the Euler grid, in the cell nearest to the location of the sensing element.

In our setup, a 500 g charge (C4) was detonated at 5000 mm distance from the pencil probe. The charge detonation and blast wave propagation was modelled in 1D (because of spherical symmetry) until arriving in the vicinity of the blast pencil probe. Then the 1D-simulation was remapped to a 3D grid. The 3D grid was uniform with cells of side length 2 mm.

Two simulations were performed; one with the blast pencil correctly aligned towards the incoming blast wave and one with a misalignment angle of 25 degrees. The latter simulation served to look at pressure-time history for both positive and negative misalignment angles.

2.2 Correctly aligned pencil probe

Let us first look at the aligned blast pencil probe. The propagation of the blast wave is shown as a contour plot in Figure 2.1. The fixed scale runs from 120 kPa (blue) to 130 kPa (red); that is roughly 20 - 30 kPa overpressure.

We see that there are some reflections close to the pencil probe and thus the pressure is slightly higher at the gauge point than it would otherwise have been. In general however, the blast pencil does a good job of not disturbing the blast wave significantly.

In Figure 2.2 we compare the pressure as a function of time at the position of the sensing element with the "correct" free field pressure (i.e. measured without any blast pencil at all).We see that a correctly aligned blast pencil overestimates slightly the peak pressure at the shock front, but for the remaining part of the wave, the agreement is perfect.
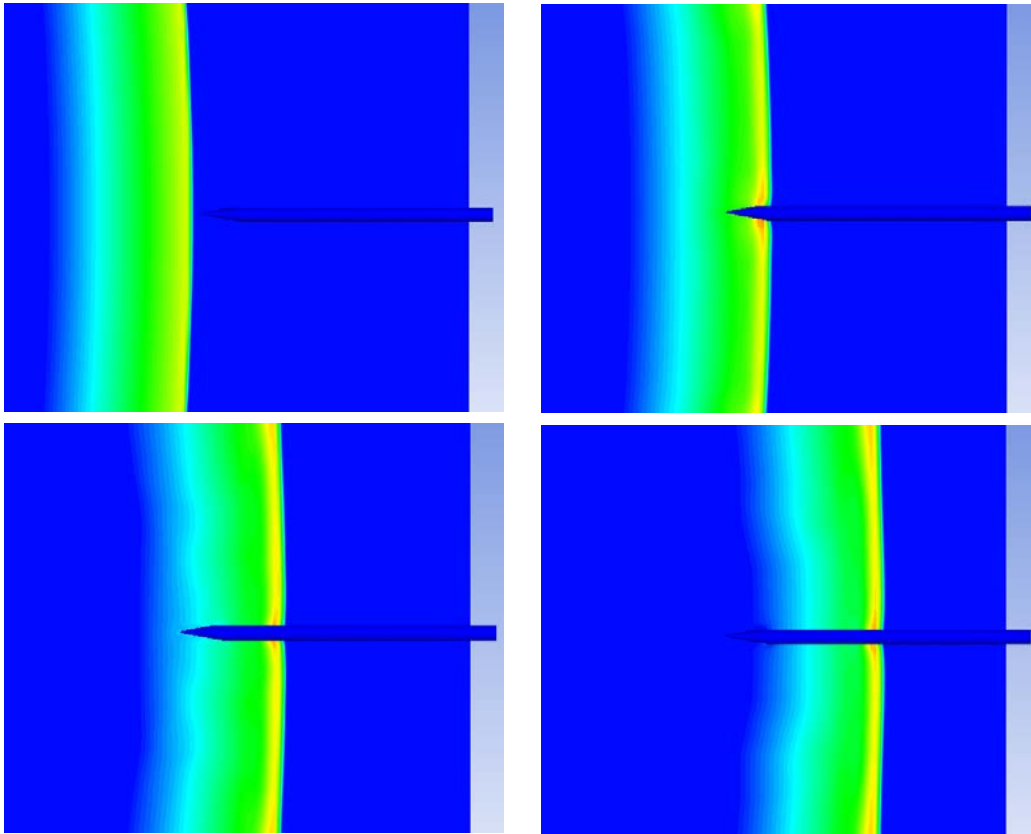
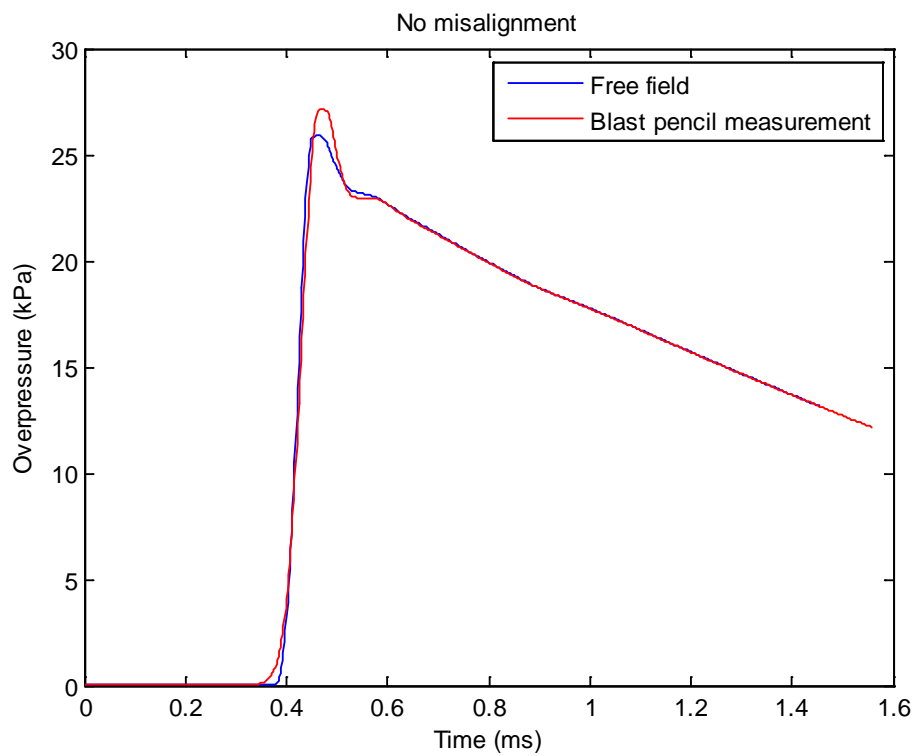*Figure 2.1   Propagation of blast wave around correctly aligned blast pencil.*

Figure 2.2   Comparison between correctly aligned blast pencil measurement and correct free field pressure.

2.3 Misaligned pencil probe

Next, let us see what happens for a 25 degree misalignment. This is shown in Figure 2.3, applying the same scale as in Figure 2.1. We observe that near the blast pencil probe, the shock wave is again disturbed by reflections. However, the amplitude increases in a larger area around the gauge than in the case for a correctly aligned pencil probe. The pressure is also larger on the side facing the blast wave, as expected.
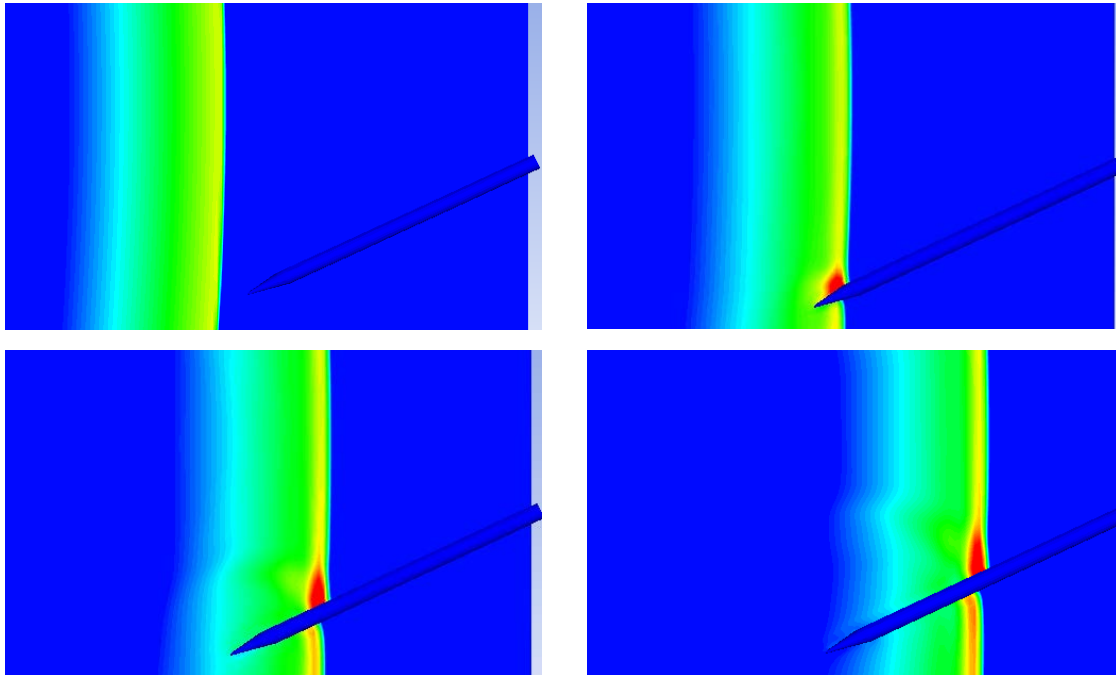

Figure 2.3   Propagation of blast wave around a 25 degrees misaligned blast pencil.

Figure 2.4 shows the pressure-time history at the position of the sensing element, as well as on the opposite side of the sensing element (representing the situation of having the sensitive element on the shadow side or having negative misalignment angle).

We first observe a similar tendency for the misaligned blast pencil measurements as for the correctly aligned blast pencil measurement (Figure 2.2): At the shock front, the peak pressure is higher than the "correct" free field pressure. About 0.2-0.3 ms after the arrival of the shock front, the agreement with the free field pressure is excellent.

As expected, a positive misalignment angle results in a higher peak overpressure than a corresponding negative misalignment angle. The peak pressure seen by a negative misalignment angle is on the other hand very similar to the peak pressure seen by a correctly aligned pencil probe. However, the negative misalignment angle results in a slightly less steep shock front.

From these observations, it is tempting to make the following hypothesis: If we know that the blast pencil has been misaligned, we can relatively easily estimate the "true" pressure-time history by ignoring the extra peak seen at the shock front and simply extrapolate the remaining pressure-time history backwards in time till intercepted by the rising edge.

Before putting this hypothesis to test, we will first try to verify our simulations by looking at experimental data.
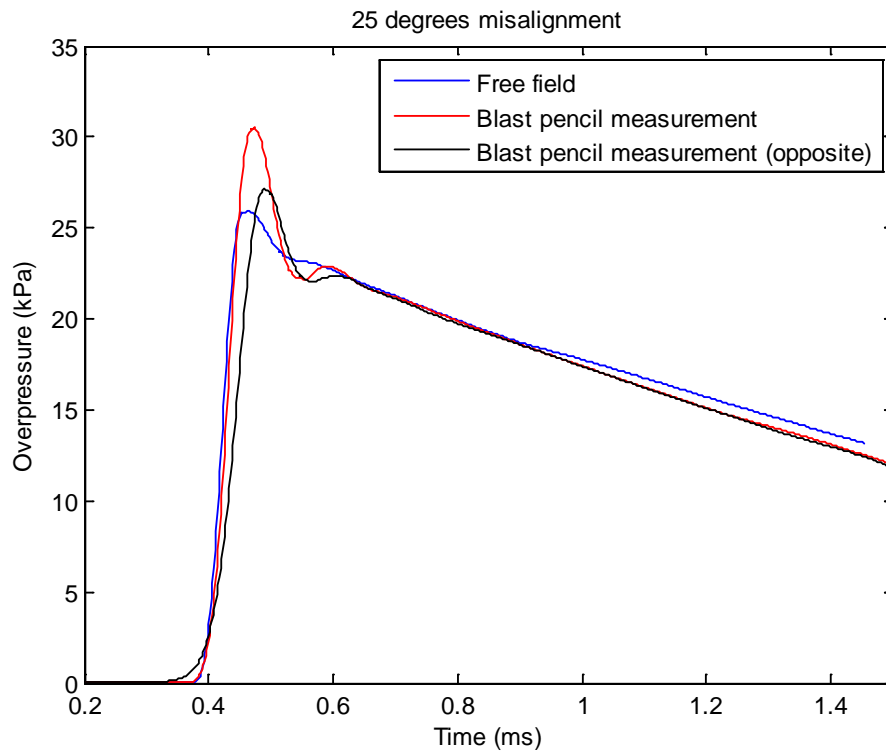

Figure 2.4 Pressure- time history from a blast pencil 25 degrees misaligned.

3 Experiments

We have seen from the simulations that misalignment seems to increase the peak pressure at the shock front, and does so for at least positive misalignment angles. Is this supported in the literature, or do we need to verify this by performing our own experiments?

3.1 Previous experimental work

There is not much data to be found in the open literature on the misalignment topic. Aberdeen Proving Grounds has conducted experiments to investigate the behaviour of the pencil probe due to misalignment. The original work is not available, but the results are indicated in reference [1] and reproduced in Figure 3.1.

This graph shows that for positive misalignment angles the peak overpressure increases. For negative misalignment angles, the peak overpressure is more or less similar to a correctly aligned pencil probe, or slightly lower. This tendency is in agreement with our simulations, although the estimated increase in peak overpressure seen in the simulation (for +25° misalignment angle) is less than indicated in Figure 3.1.
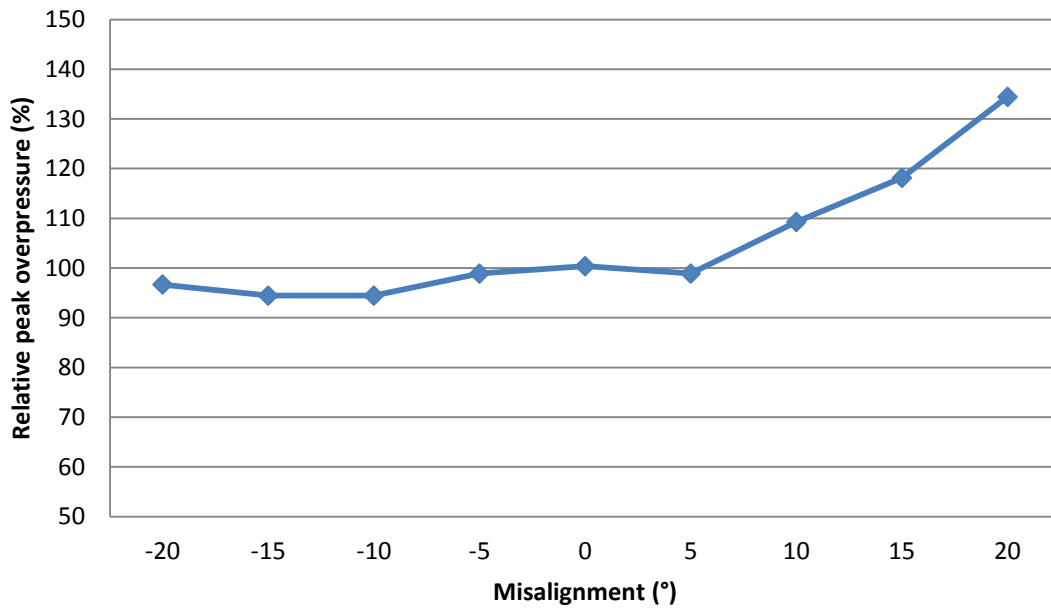
*Figure 3.1   Relative peak overpressure as function of misalignment for tapered pressure probe.
Reproduced from Technical note TN-27 [1].*

In reference [1], there is no information about how the tests at Aberdeen Proving Grounds were performed. Hence, we do not know the actual setup, the pressure levels measured etc. Consequently, we decided to conduct a limited test series.

3.2   Setup

Since the boundary conditions of the previous experimental work are not known in detail, we decided to conduct our own experiments. The setup is shown in Figure 3.2 and Figure 3.3.

The pencil probes were mounted on wooden stands with the sensing diaphragm 5 m from a circle's origin (*O*). The angular distance between each pencil probe (*Δα*) was 30°, hence in total twelve gauges were fitted into the circle. The pencil probe height above ground was about 1.6 m. The explosive charges were positioned at *O*, and at the same height as the pencil probes.

The pencil probes were numbered from 1 to 12 and the misalignment angle for each sensor (ranging from -25° to +25°) is indicated in Figure 3.3. Each pencil probe was aligned (or misaligned) using a triangle *AOB*. The sensing element was positioned exactly at *A*, and the pencil probe was pointed towards *B* using a laser pointer. The distance *OB* was determined based on the requested misalignment angle.

Figure 3.2   Picture from the misalignment tests showing the circular setup of the pencil probes mounted on the wooden stands, with a similar stand for the explosive charge at the centre.
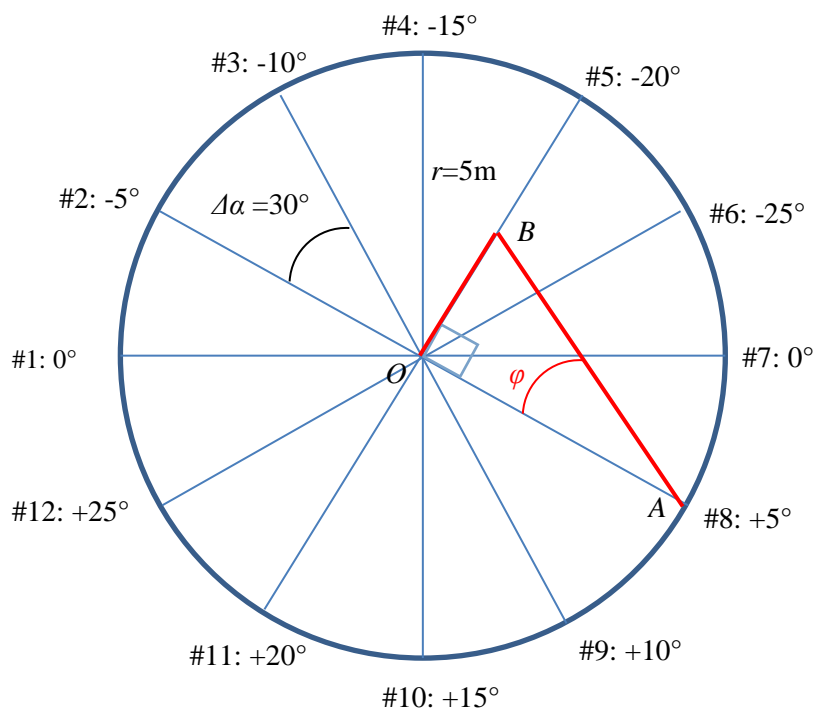

Figure 3.3   Misalignment test shown schematically.

Table 3.1 summarizes the key figures for each pencil probe orientation. Negative distance *OB* and angles φ indicate a negative misalignment angle.

Table 3.1   Measured distance OB and the actual misalignment angle for each pencil probe.

Sensor no.	Misalignment angle φ - aim (°)	Measured distance OB (cm)	Misalignment angle φ - actual (°)
#1	0	0	0
#2	-5	-45	-5.1
#3	-10	-88	-10.0
#4	-15	-133	-14.9
#5	-20	-182	-20.0
#6	-25	-233	-25.0
#7	0	0	0
#8	+5	45	+5.1
#9	+10	88	+10.0
#10	+15	134	+15.0
#11	+20	182	+20.0
#12	+25	233	+25.0
Uncertainty		± 5	± 0.6°

3.3 Experimental results

In total 8 charges were detonated in the test campaign. The two first detonations served as reference measurements (R1-R2). In these tests, all blast pencils were oriented directly towards the charge. The remaining six detonations were the actual misalignment tests (M1-M6) using the setup as described above. The charge consisted of handmade spheres (or as close to spheres as achievable) of C4 high explosives. The masses and expected peak overpressure is given in Table 3.2, the latter values are based on calculations using equations and software in references [4;5].

Table 3.2   C4 charge sizes used in the experiments [4;5].

Test no.	Charge size (g)	Expected peak overpressure at 5 m (kPa)
R1	500	24
R2	500	24
M1	100	11
M2	250	17
M3	500	24
M4	1000	35
M5	2500	61
M6	5000	98
Uncertainty	± 5	

The uncertainty in the measured distance from the blast source to the pencil probe is estimated to be ± 0.1 m. This will lead to an uncertainty in the peak overpressure. Using the same software as

above, this is estimated to be less than ± 4 % for the charge sizes under consideration. The expected change in peak overpressure due to the uncertainty in the charge size is negligible.

The shape of the charge was not perfectly spherical, as it was handmade at the test site. However, the distance from the charge centre to the measurement location (5 m) was much larger than the charge radius. Hence it is assumed that the uncertainty in the measured peak overpressure due to the non-perfect spherical shape can safely be neglected. The same argument applies for the positioning of the detonators which were put roughly at the charges' centre.

All pressure-time history curves are plotted in Appendix A. In the following subsections, only examples or evaluated data will be presented.

All pressure measurements were sampled at 1 MHz sampling frequency.

3.3.1   Reference shots

The reference shots serve to disclose:

- Any pencil probe failure prior to the misalignment tests;
- Individual variation between two similar shots;
- Systematic variation in pressure readings between the different pencil probes.
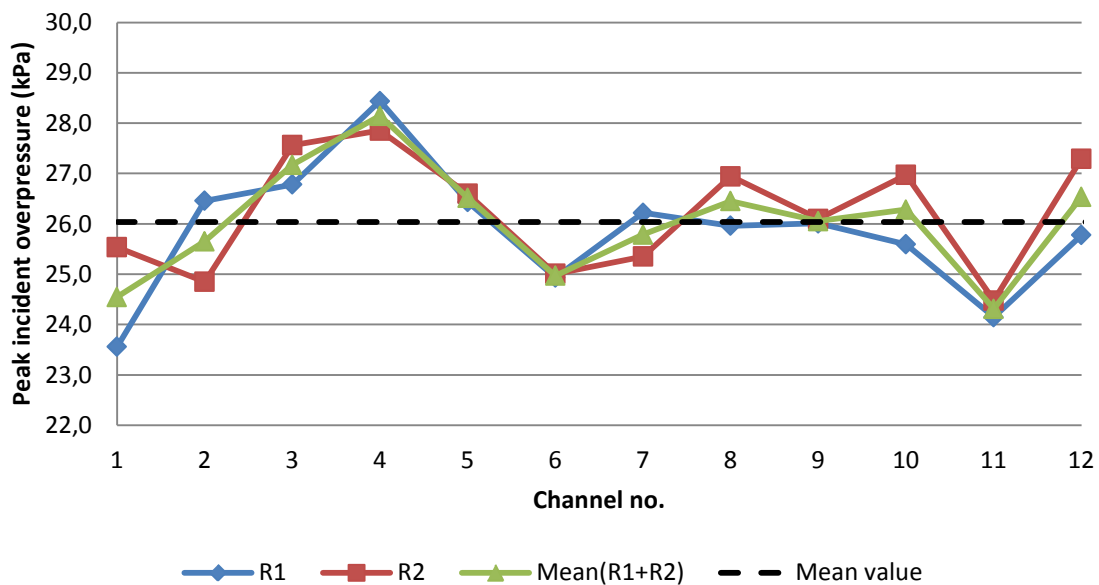
Figure 3.4   Peak overpressure (unfiltered data) measured by the twelve pencil probes pointing towards the 500 g C4 charge. Black solid line indicates the overall mean value (26 kPa).

In total two reference shots were performed, both with a charge size of 500 g C4. Figure 3.4 shows the extracted peak pressure value (from unfiltered data) for each pencil probe numbered 1

to 12 (see Figure 3.3). Both reference shots (R1 and R2) are indicated together with each sensor's mean value. The maximum individual variation from the two shots is less than ± 4 %.

A black solid line indicates the overall mean peak pressure value. Maximum deviation from this overall mean value is ± 8 %.

Compared to the theoretically calculated and expected peak overpressure (Table 3.2), all sensors show higher readings.

3.3.2   Misalignment tests

The misalignment shots serve to disclose:

- Changes to the pressure-time history curve due to misalignment;
- Misalignment effect due to change in charge size;
- Possible ad-hoc methods to compensate for a misalignment effect.

First, let us look at the change to the pressure-time history curve due to misalignment. Figure 3.5 shows the result for the 500 g C4 charge (M3). This measurement is comparable to the AUTODYN simulations in section 2. On the top, the pressure-time history of the two correctly aligned pencil probes is shown. They are more or less identical.

In the middle, the pressure-time history curves for the pencils having negative misalignment angles are shown. We observe a minor increase in peak pressure for increasing misalignment angle.

In the bottom, the pressure-time history curves for the pencils having positive misalignment angles are shown. Here we can clearly see that the pressure readings in the first 40 µs after arrival of the shock front deviate from the correctly aligned pencils. The rest of the pressure-time history seems to be more or less identical.

We also observe that the misalignment effect is more evident for positive misalignment angles than for negative misalignment angles. Similar observations can be made for the other charges tested and plotted in Appendix A. These findings are in good agreement with the tendencies observed in the simulation; however the calculated peak overpressure (for +25° misalignment) is smaller than measured.

We may conclude that the misalignment effect seems to be a "problem" only at the shock front. Hence, a good parameter to study is the peak overpressure, or the change in peak overpressure.
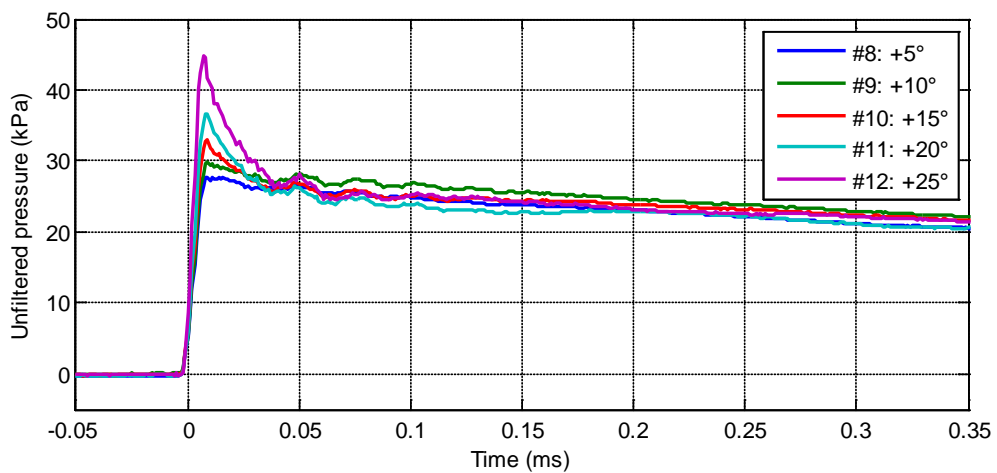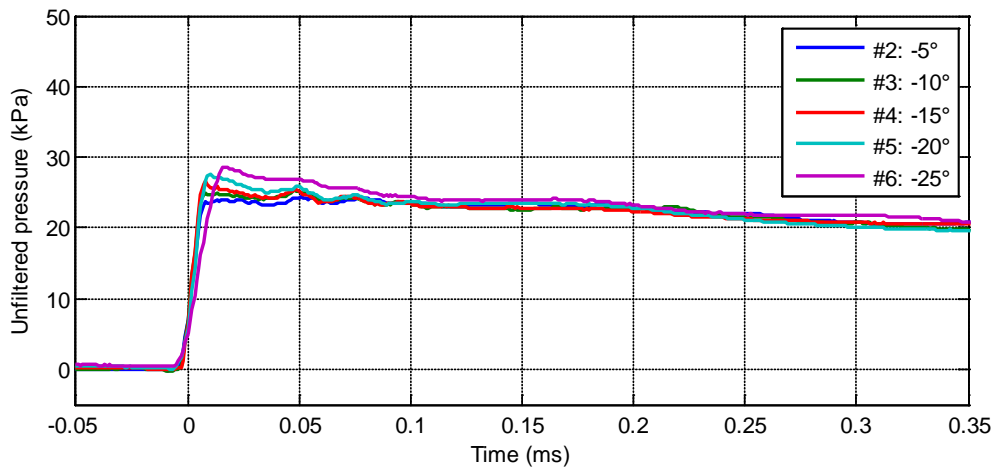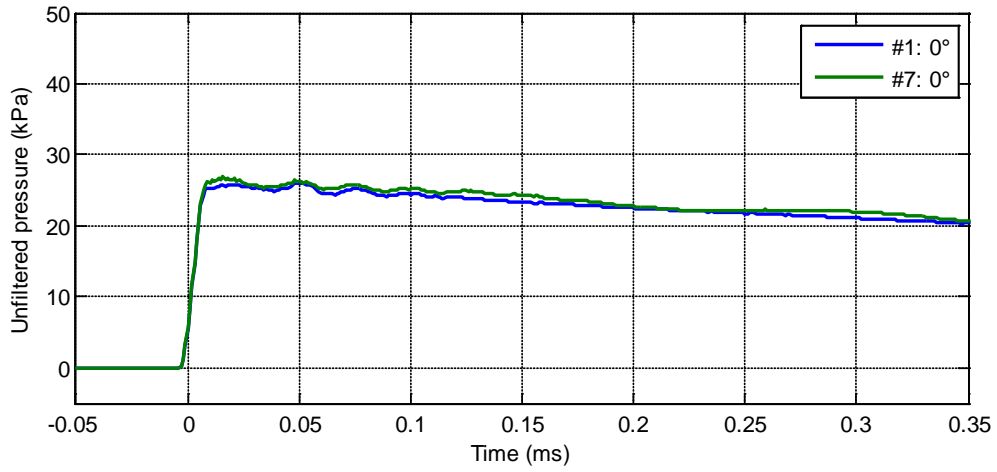
Figure 3.5   Pressure-time history curves for a 500 g C4 charge. Top: Pencil probes correctly aligned. Middle: Negative misalignment angles. Bottom: Positive misalignment angles.

Table 3.3 shows the mean peak overpressure measured by the two correctly aligned pencil probes (number 1 and 7) and the deviation from the calculated peak overpressure (Table 3.2) using empirical equations [4;5]. We observe that the measurements generally result in higher peak pressure than calculated, except for shot number M6. Whether this is a normal variation or a result of some failure is not known as only one shot was made with a 5.0 kg charge size.

Table 3.3   Deviation from the expected peak overpressure.

Test run	Expected peak overpressure at 5 m (kPa)	Mean peak overpressure for sensors correctly aligned (kPa)	Deviation (%)
M1	11	11,7	+6
M2	17	17,8	+5
M3	24	26,5	+10
M4	35	35,1	0
M5	61	63,5	+4
M6	98	89,6	-9

In Figure 3.6, the relative peak overpressure is plotted as a function of misalignment angle for varying charge size. The overall trend seems to be similar for all charge sizes. Both negative and positive misalignment angles increase the peak overpressure value. The effect is most distinct for the positive angles. Compared to the individual and overall variations seen in the reference shots (Section 3.3.1), and hence also expected in the misalignment tests, this data set is considered fairly congruent.
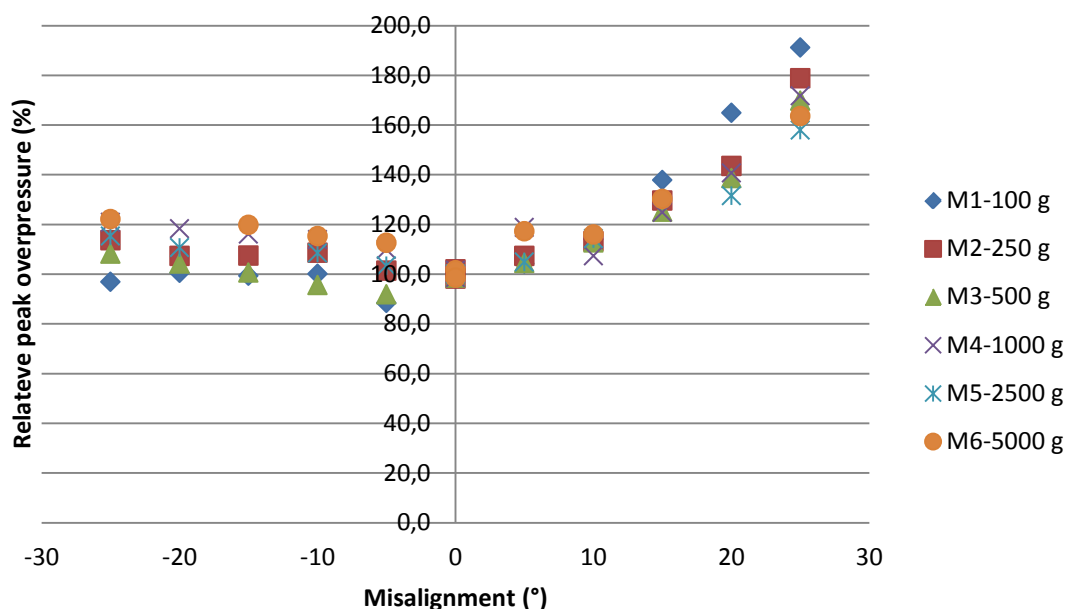

Figure 3.6   Relative peak overpressure as function of charge size and misalignment angle (φ).

Looking at the data more closely, the negative misalignment angles influence the peak overpressure more and more as the charge size increases, whilst the opposite appears to be the case for positive misalignment angles.

The relative size of the sensor compared to the blast wave length is smaller when the charge is smaller. Hence, it is to be expected that the sensor is a larger obstacle for blast waves from smaller charges, thus giving larger reflection overpressures. On the other hand, the increased non-linearity in the larger charges contributes in the other direction. The balance between these two mechanisms may explain why the relative peak overpressure seems to be relatively constant at high misalignment angles, for different charge sizes. More work would be needed to support this hypothesis.

Figure 3.7 shows the relative peak overpressure averaged over all charges, as function of misalignment angle. We have added the curve from Figure 3.1 for comparison. This shows that misalignment angles less than 10 ° results in a peak overpressure error of less than 13 %.
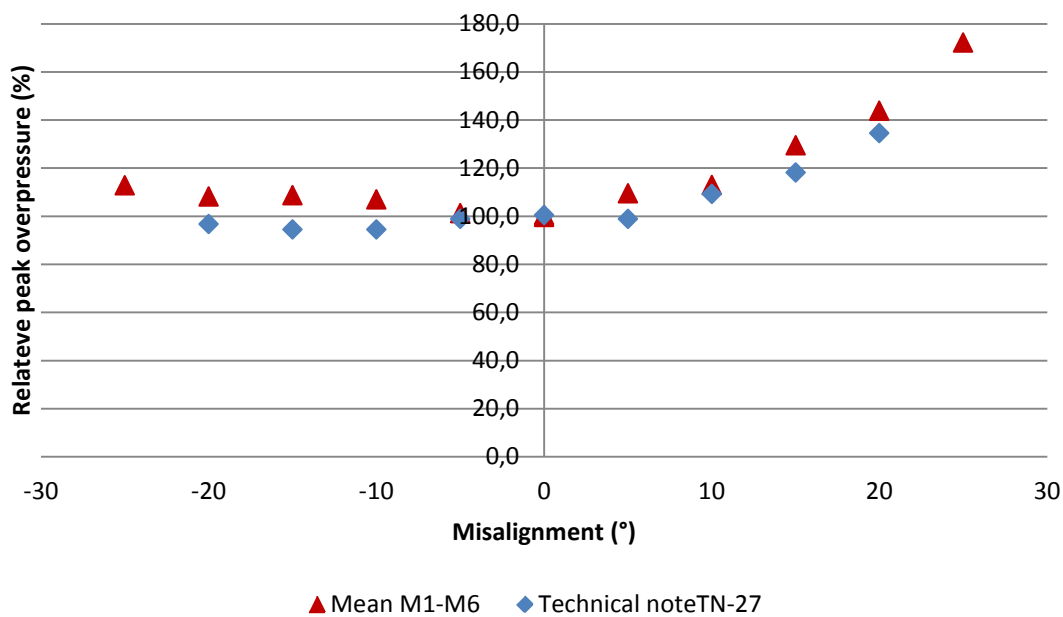
Figure 3.7   Relative peak overpressure averaged over the charge sizes 0.1 to5 kg. The experimental result is compared to data from Figure 3.1.

Compared to the misalignment data reported by Walter [1] and discussed in Section 3.1, our findings indicate a slightly higher misalignment effect, especially for the negative angles. However, it must be stressed that our data set is perhaps too scarce to make a categorical conclusion.

Based on this figure, a maximum acceptable misalignment angle could be established. However, the degree of accuracy needed might differ from situation to situation. Hence, a general conclusion or recommendation cannot be made.

3.4 Frequency analysis

A frequency analysis is used to transform the measurement from time domain to frequency domain. Data filtering is further used to remove unwanted frequencies, and the cut-off frequency is often chosen by first investigating the frequency components.

It is of great interest to look for changes in the frequency domain due to misalignment. If there is an evident change in the frequency domain for a misaligned pencil probe, compared to the correctly aligned pencil probe, we could filter the data to compensate for this effect while keeping in mind that we might at the same time degrade the relevant signal.

As an example, we look at test run M5 (2.5 kg C4). We use a Fast Fourier Transform (FFT) method to transform the time series to the frequency domain. Then, we display the 1/3-octave spectra of the sound exposure level (SEL) [6].

In Figure 3.8 we see the spectrum found from the time series starting at -2 ms and ending at 60 ms for the two sensors pointing directly towards the blast source. We have removed a linear trend caused by the normal drift of the sensors. As they are both correctly aligned, they should measure similar pressure-time histories. This plot, however, highlights a common problem with the pencil probe (PCB 137A23) used in this test series. We see that there are oscillations at around 300 and 1000 Hz on sensor no. 7 but not in sensor no. 1.
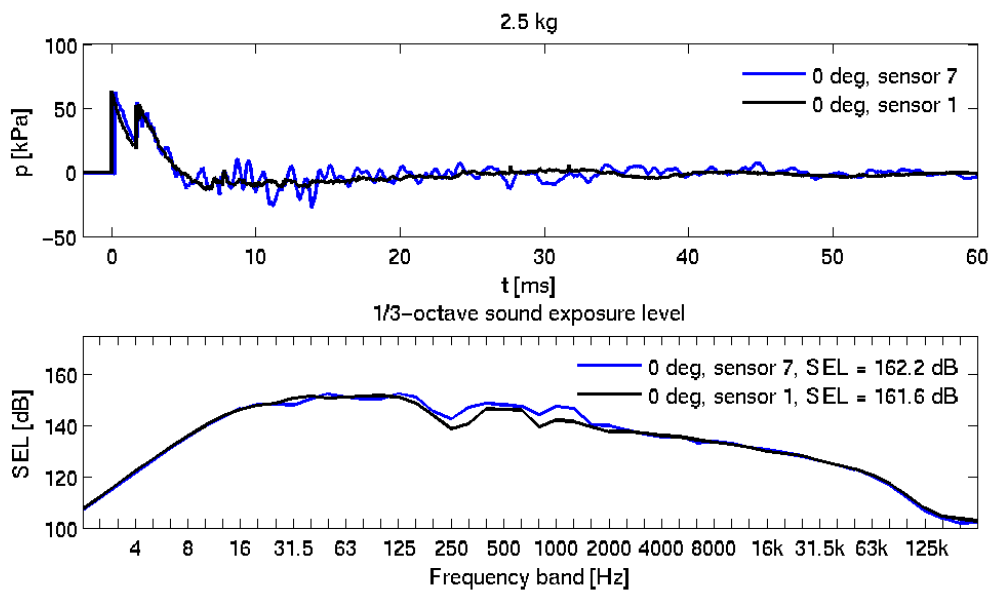
Figure 3.8   Example of variations in measurements with PCB 137A23. The two sensors are both correctly aligned. One sensor has oscillations around 300 and 1000 Hz.

In Figure 3.9 we compare the 1/3-octave spectra for six different misalignment angles. What we observe from this figure is that the measurements are reasonably similar, except for the high frequency peak especially for large angles (+20 and +25 degrees). We see that the difference is most noticeable for frequencies larger than about 8 kHz. We thus expect the signals to look

reasonably similar if the pressure-time history curves was filtered using a low pass filter with a cut-off frequency around 8 kHz .
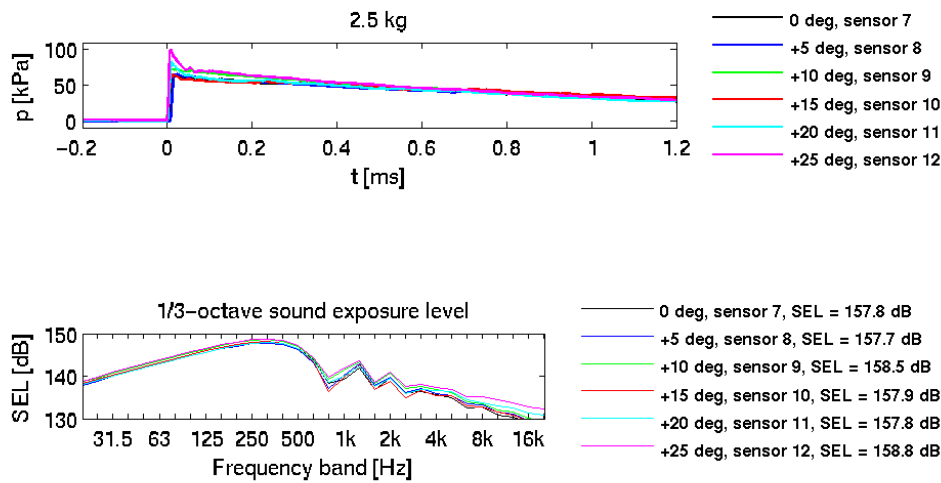

Figure 3.9   Comparison of 1/3-octave frequency spectra for misalignment angles 0 to +25°.

3.5   Filtering

In order to investigate the above findings, we apply a low-pass 4-pole Bessel filter, with different cut-off frequencies, to the pressure-time history for the +25° misaligned pencil probe. The cut-off frequency is varied from 100 kHz down to 6 kHz. We compare the results with the unfiltered signal and the unfiltered signal from a correctly aligned blast pencil, pencil no. 1.

The results, for shot M3 and M5 (500 g and 2500 g C4 high explosives respectively) are seen in Figure 3.10. The remaining plots can be found in Appendix A.
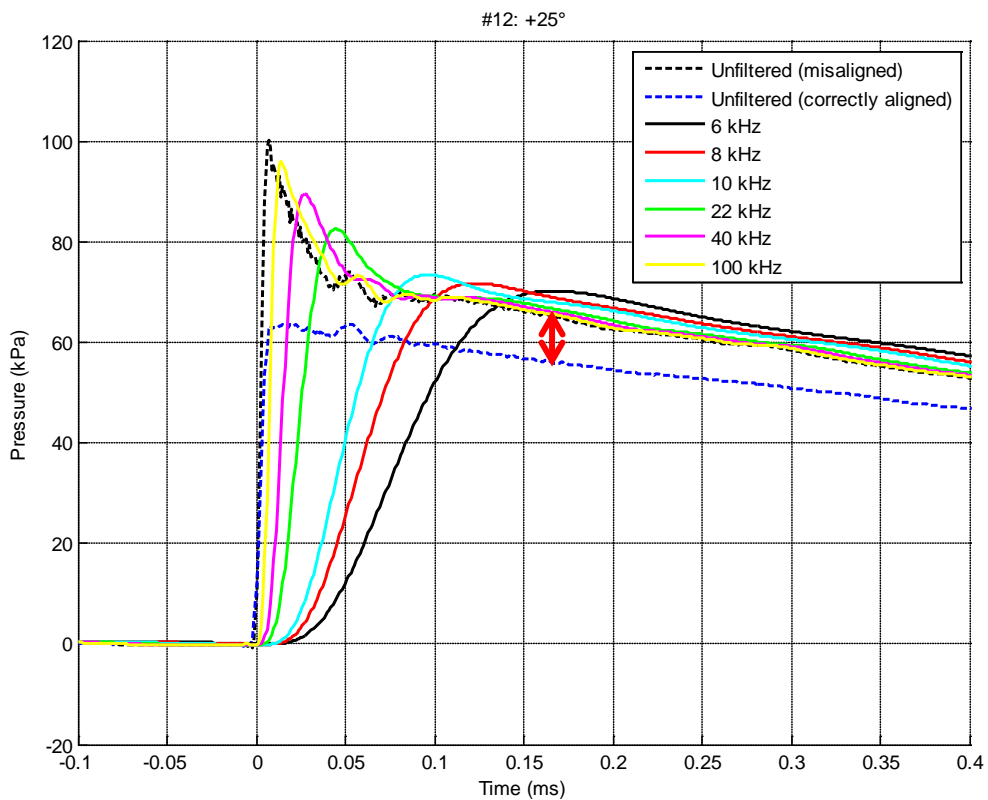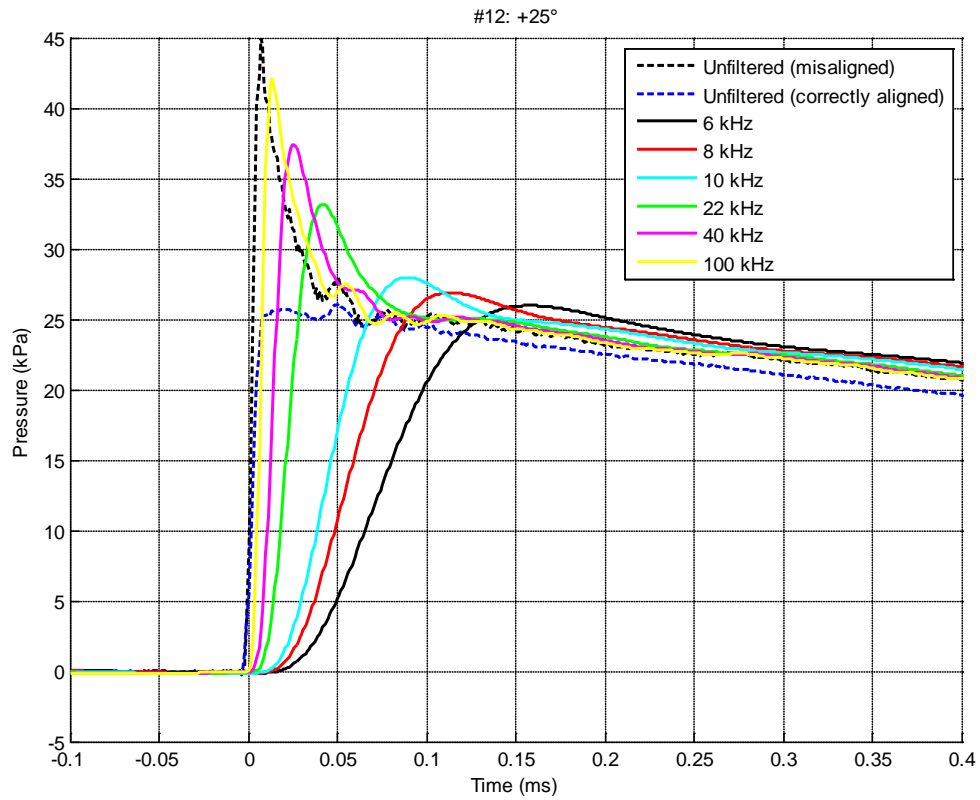
Figure 3.10 Filtering of blast pencil no. 12 (+25° misaligned). Top: M3 (500 g C4). Bottom: M5 (2500 g C4). Note red arrow indicating a generally lower pressure time history seen for the larger charge size.

Before we proceed with some assessment of the filtering procedure, the reader might already have observed that the pressure-time history of the correctly aligned pencil probe, in shot M5, is generally lower than the readings from the misaligned pencil probe, and not only in the shock front. This is indicated by a red arrow in the figure above. In fact, similar tendency is seen in Figure- A.16 (5 kg charge), but not for the smaller charges (100 g – 1 kg). If all pencil probes having positive misalignment angles are studied and compared to the correctly aligned pencil probes (see figures in Appendix A) the following could be observed:

- The overall pressure-time history curve for the misaligned pencil probes seem to increase with increasing misalignment angle in shot M6 (5 kg C4);
- The overall pressure-time history curve for some misaligned pencil probes seem to be higher than the correctly aligned pencil probe in shots M4 and M5 (1 kg and 2.5 kg C4, respectively), however it does not seem to be correlated with the misalignment angle;
- All pressure time-history curves merge after about 0.9 ms, after the arrival of the shock front.

Could these observations be explained physically or is it just a coincidence (within "normal" variations of our experiments)? It seems for the moment difficult to answer this question due to the limited number of firings, and the fact that we did not test each charge size more than once. However, we should keep this in mind when calculating the relative change in peak overpressure.

Moving back to the filtering procedure, we see that when using a cut-off frequency of 10 kHz or lower, it removes the peak at the shock front caused by the misalignment. This is to be expected from the findings above. But, at the same time the shock front is degraded (becomes less steep) because all the high frequency components are removed.

As an example, the 8 kHz low-pass filter degrades the shock front by increasing the rise time from about 10 µs to about 100 µs. Comparing the rise time to the positive phase duration of the signal, about 2.5-3 ms, the degradation is not alarming. Hence, if only the peak overpressure is of interest, the filtering method should be considered acceptable. However, if the rise time of the shock front is also of importance for the assessment, one should use this procedure with uttermost caution.

4   Correction methods

We have seen that the result of having misaligned pencil probes seems to be an extra peak at the shock front. We have also seen that it is possible to remove this peak by applying a low pass filter, allowing the analysis to be automated, but at the expense of degrading the shock front. Is there another method which could be used?

Let us now readdress the hypothesis proposed at the end of section 2.3. Is it possible to estimate the "true" pressure-time history by ignoring the extra peak seen at the shock front and simply extrapolate the remaining pressure-time history backwards in time till intercepted by the rising edge?

In Figure 4.1, the proposed ad-hoc method above is illustrated. The red line indicates the "by hand" backwards extrapolation of the unfiltered misaligned signal. The interception point with the rising edge is indicated. For comparison, the unfiltered signal from the correctly aligned pencil probe is added. Note that in addition to predicting the peak overpressure quite accurate, the method does not influence the rise time which is the case for the filtering procedure.
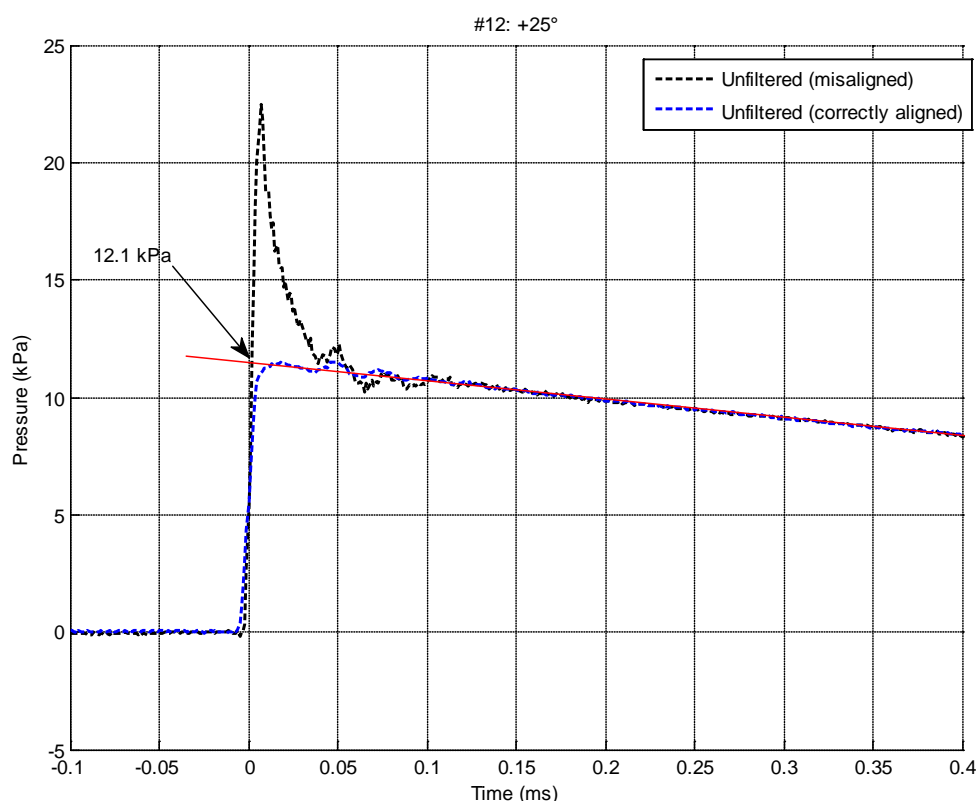
Figure 4.1   Example of how to find the corrected peak overpressure with the "by hand"-method. Example shown is from test run M1 (100 g C4) and using the pencil probe misaligned at 25°.

For the specific example shown above, the result is remarkable. However, we may not be that lucky for the other tests performed. Let us therefore do this exercise for all tests performed (M1-M6), still focusing on the +25° misaligned probe. The corrected peak overpressure as function of charge mass is shown in Figure 4.2. For comparison, the results after filtering with low pass filter with different cut-off frequencies are added.

From this figure, the following conclusions can be drawn:

- Filtering using 6-10 kHz low-pass filter gives roughly the same result as the "by hand"-method, when comparing the peak overpressure;
- Filtering using a low-pass filter with a cut-off frequency larger than 10 kHz seems (in our experiments) not to be sufficient to remove the extra peak due to the misalignment;
- The corrected peak overpressure is better approximated for smaller charges than larger charges;
- For small charges (1 kg C4 and less) and +25 ° misalignment, the "by hand" procedure gives an peak overpressure up to 8 % higher than the correctly aligned pencil probe;
- For larger charges (2.5 and 5 kg) the peak overpressure is still 20-30 % higher than the peak pressure measured with the correctly aligned pencils.
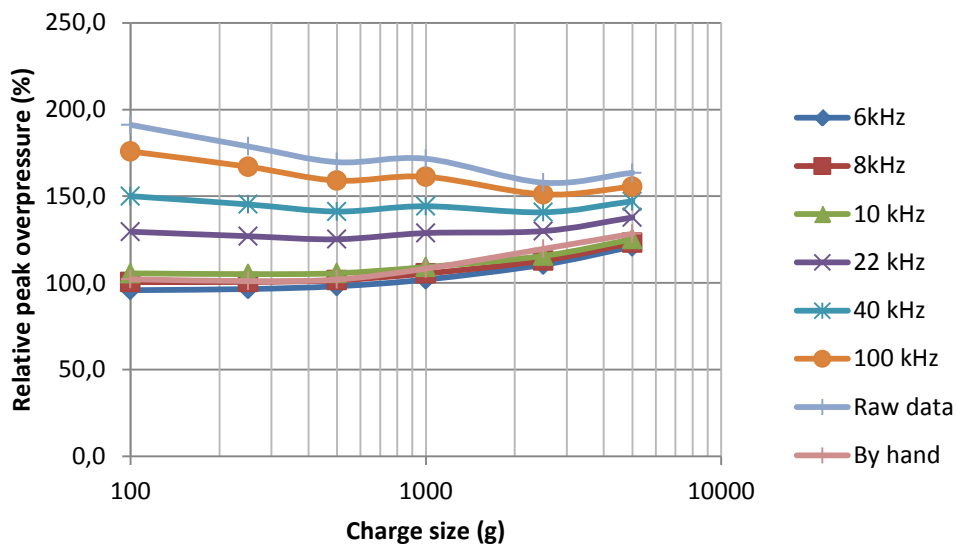
Figure 4.2   Relative peak overpressure for +25 ° misaligned pencil probe. Various cut-off frequencies are compared to "by hand"-method.

Since the filtering procedure with a 10 kHz cut-off frequency gives results similar to the "by hand" method, we try this Bessel filter to all charges and all positive misalignment angles. The results (relative peak pressure) are seen in Figure 4.3, together with a linear fit.

From this figure we see that:
- The general trend is that the relative peak overpressure increases for increasing charge size. This is in agreement with the observed change in pressure-time history curve pointed out in Figure 3.10 and discussed in section 3.5. The data set is too scarce to verify if this is a physical effect or just a stochastic variation, hence no procedure is proposed to compensate for this observed increase;
- Again, the corrected peak overpressure is better approximated for smaller charges than larger charges;

- For charges of 1 kg and less, the corrected peak overpressure is fairly accurate and differs only from -4 % to 13 % with respect to the correctly aligned pencil probe;
- For charges larger than 1 kg, the corrected peak overpressure differs from -3 % to 25 % with respect to the peak overpressure measured by the correctly aligned pencil probe;
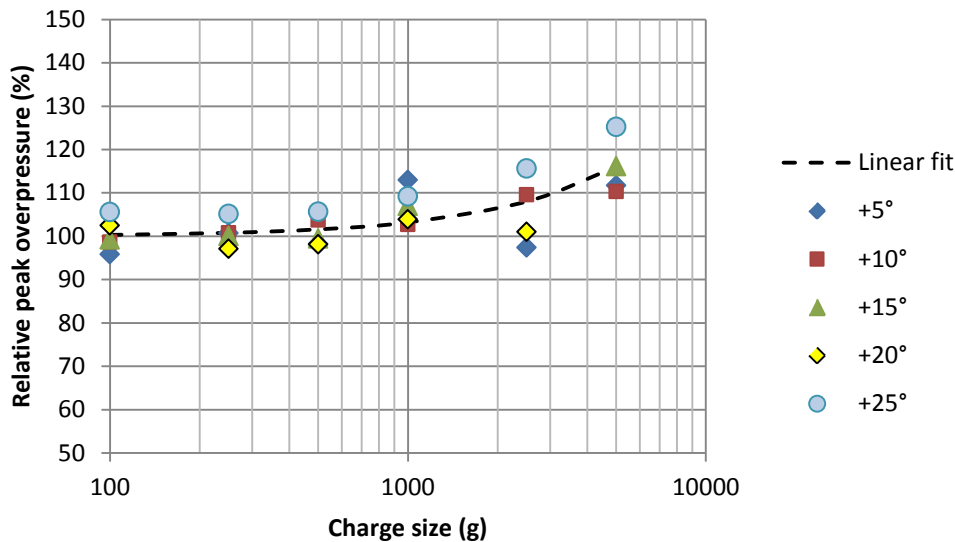- Although some variation in the data points, it seems to be possible to compensate for a misalignment angle.

Figure 4.3   Relative peak pressure as function of charge size for the various positive misalignment angles after being filtered by 10 kHz low-pass Bessel filter.

5   Summary and conclusions

The correct way to use the pencil probe is to let the probe tip point upstream the propagating blast wave. This is trivial in some cases, but is not in other situations, e.g. when we are dealing with a non-static blast source, several blast sources or with a complex blast environment having several reflected waves impinging the blast sensors. Hence, in some situations there is a high risk for the pencil probe to be misaligned.

Although the pencil probe is not the optimum choice in these situations, we investigate the misalignment effect by performing simulations and experiments. In our measurements we have kept the source-to-sensors distance constant at 5 meters, but varied the charge size. The test charges are in the range 100 g – 5 kg. This gives a peak overpressure roughly between 10 and 100 kPa for a correctly aligned pencil probe.

The misalignment effect seems to vary as a function of two dimensionless variables, i.e. the ratio between the length scale of the pressure wave and the sensor size, and the overpressure to ambient pressure ratio. We have only done measurements along one curve in this two-dimensional plane. For a broader investigation of the "misalignment effect" we would need to vary both the charge size and the source-to-sensor distance.

First, we address what happens when the pencil probe is misaligned: Both from the simulations and from the experiments we see that the pressure amplitude is overestimated at the shock front. This seems to happen for both negative and positive misalignment angles, although the effect is more pronounced for positive ones. Except for the peak at the shock front, the agreement between the correctly aligned pencil probes and misaligned pencil probes is very good.

Some exceptions are still seen in the experiments for the larger test charges, where the pressure-time history curves for some misaligned pressure probes seem to be overall higher than the readings from the correctly aligned pressure probe. We realize, however, that our data set is too scarce to disclose whether this is a stochastic variation or a physical effect dependent on parameters such as pressure amplitude or wave length scale.

The overestimation of peak overpressure, due to misalignment, seems to be slightly dependent on the charge size. However, when looking at the mean value for all charges tested, we see that a misalignment between -10° to +10° results in an error of less than 13 %, which is in the range of shot-to-shot variations plus other sources of error. The maximum acceptable misalignment angle is of course dependent on the required accuracy.

In order to compensate for, or make corrections to, the misalignment effect we introduce both a filtering procedure and a "by hand"-method. In the filtering procedure, the cut-off frequency should be decided from the frequency analysis. However for the charges herein, 8 or 10 kHz seems to be a good choice. The rise time of the shock front will be slightly degraded when using the filtering procedure, so care must be taken if this is important for the assessment. The "by hand"-method gives similar results for the corrected peak overpressure as the selected low-pass filter method, and it does not alter the rise time of the pressure-time history.

If the filtering procedure or "by hand"-method is used to correct the peak overpressure, the error of the pencil probe is less than 13 % for smaller charges, while still 15-30 % for larger charges. Whether the observed increase in overestimation is a physical effect or just a stochastic variation in our limited data set is not known, hence no procedure is outlined to compensate for this effect.

References

[1] Walter, P. L., "Measuring static overpressure in air blast environments," PCB Piezotronics Inc., Technical note (TN-27), 2013. [Online]. Available: http://www.pcb.com/techsupport/ [Accessed: 1-2-2013].

[2] "Model 137A23 Free-Field ICP Blast Pressure Sensor - Installation and Operating Manual," 2012. [Online]. Available: http://www.pcb.com [Accessed: 6-8-2012].

[3] "Electronic Measurement of Airblast Overpressure and Impulse Noise,"FR/GE/US International Test Operations Procedure (ITOP) 4-2-822, 2000.

[4] K. Holm, "Ny håndbok i våpenvirkninger - sluttrapport fra FFI-prosjekt 803.01,"FFI/RAPPORT-2003/00070, 2003.

[5] J. O. Langseth, K. B. Holm, J. A. Teland, S. Christensen, S. Martinussen, and H. Sjøl, "Trykkbølger i luft," in *Håndbok i våpenvirkninger*. L. Riis, K. B. Holm, and J. Ommedal, Eds. Forsvarsbygg, 2003.

[6] "Electroacoustics - Sound level meters - Part 1: Specifications,"International standard IEC 61672-1, 2002.

Appendix A   Pressure-time history curve

In this appendix, all unfiltered pressure-time history plots, from the two reference shots and six misalignment shots, are shown.

We have also plotted the filtered pressure-time history curve, originating from the +25 ° misaligned pencil probe, using different cut-off frequencies and compared it with the unfiltered data and unfiltered data from a correctly aligned pencil probe.
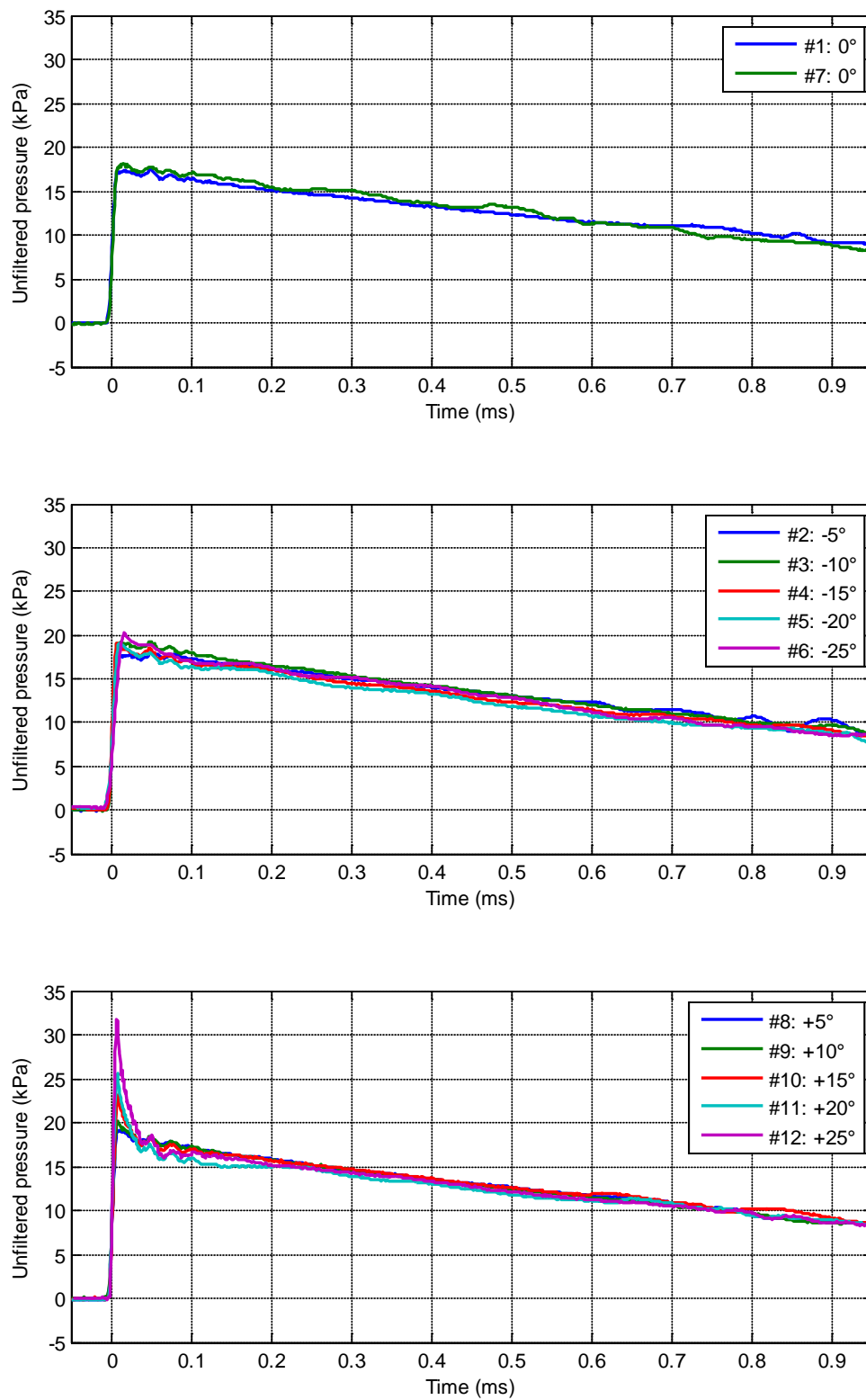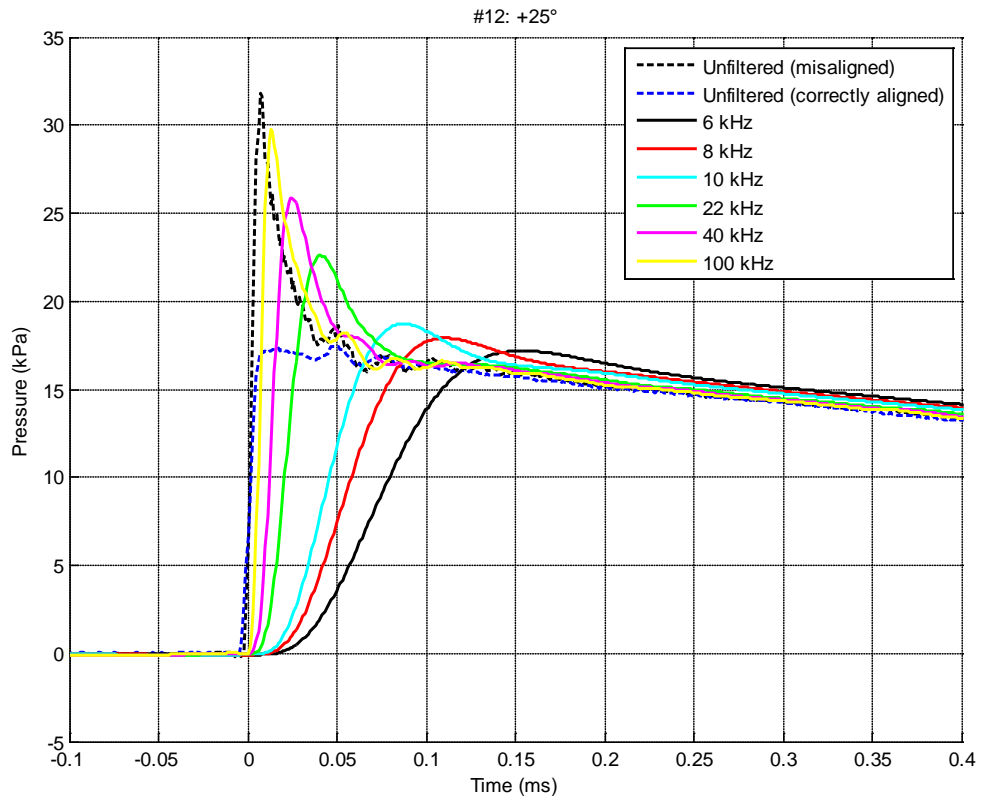
A.1 R1 – 500 g C4
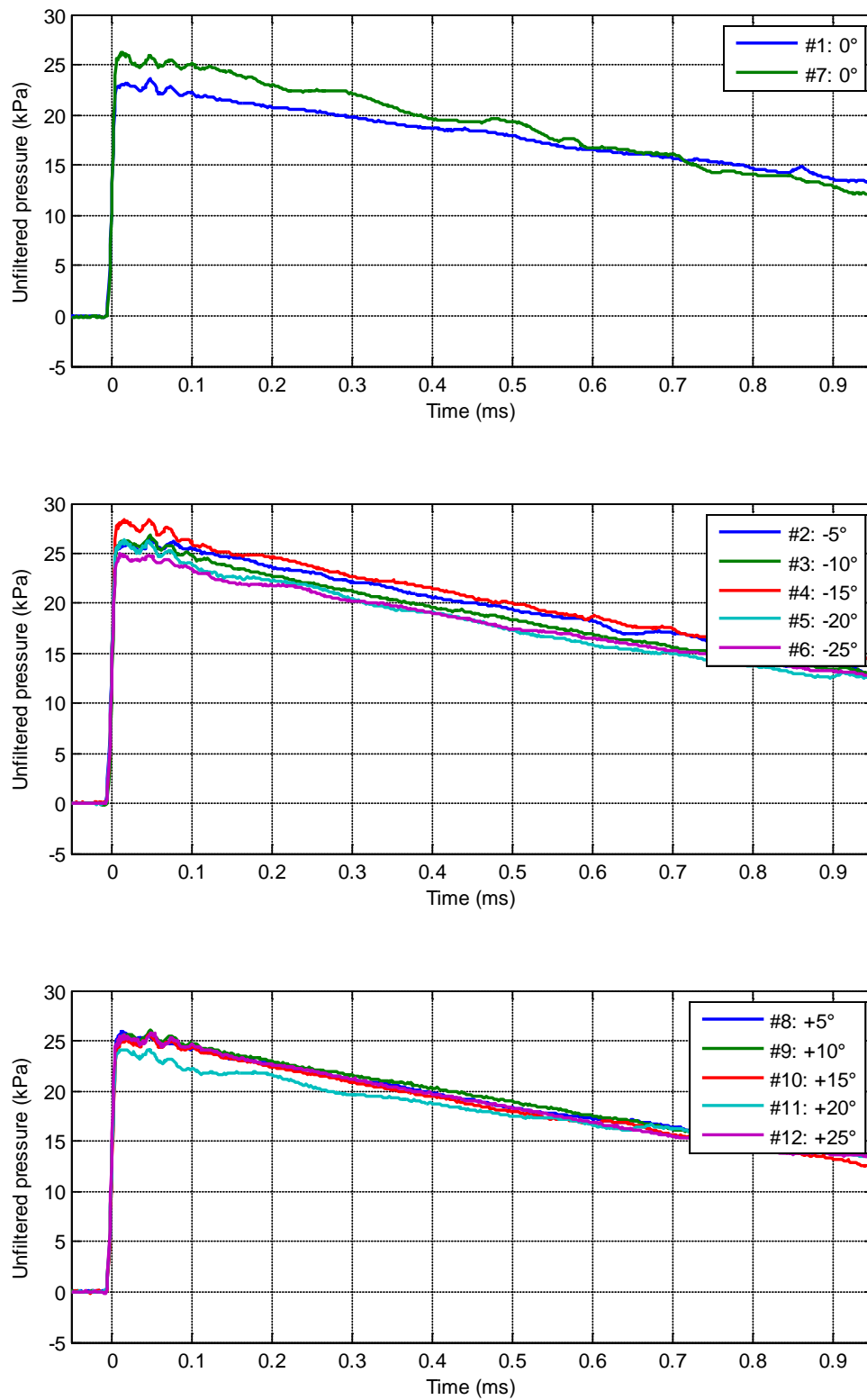
Figure A.1 Unfiltered data.
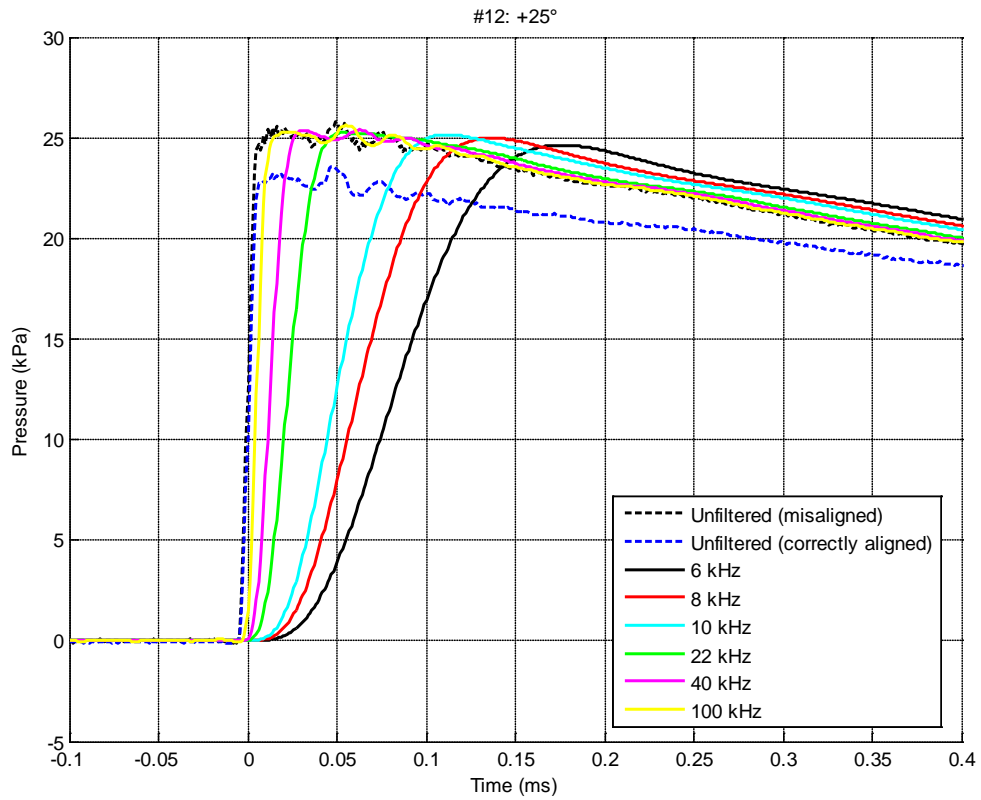
Figure A.2   Pressure-time history plot from pencil probe misaligned at +25°. Filtered data, using varying cut-off frequencies, are compared to unfiltered data and unfiltered data from a correctly aligned pencil probe. Note that the correctly aligned pencil probe seems to overall yield lower pressure-time data than the +25° misaligned pencil probe.
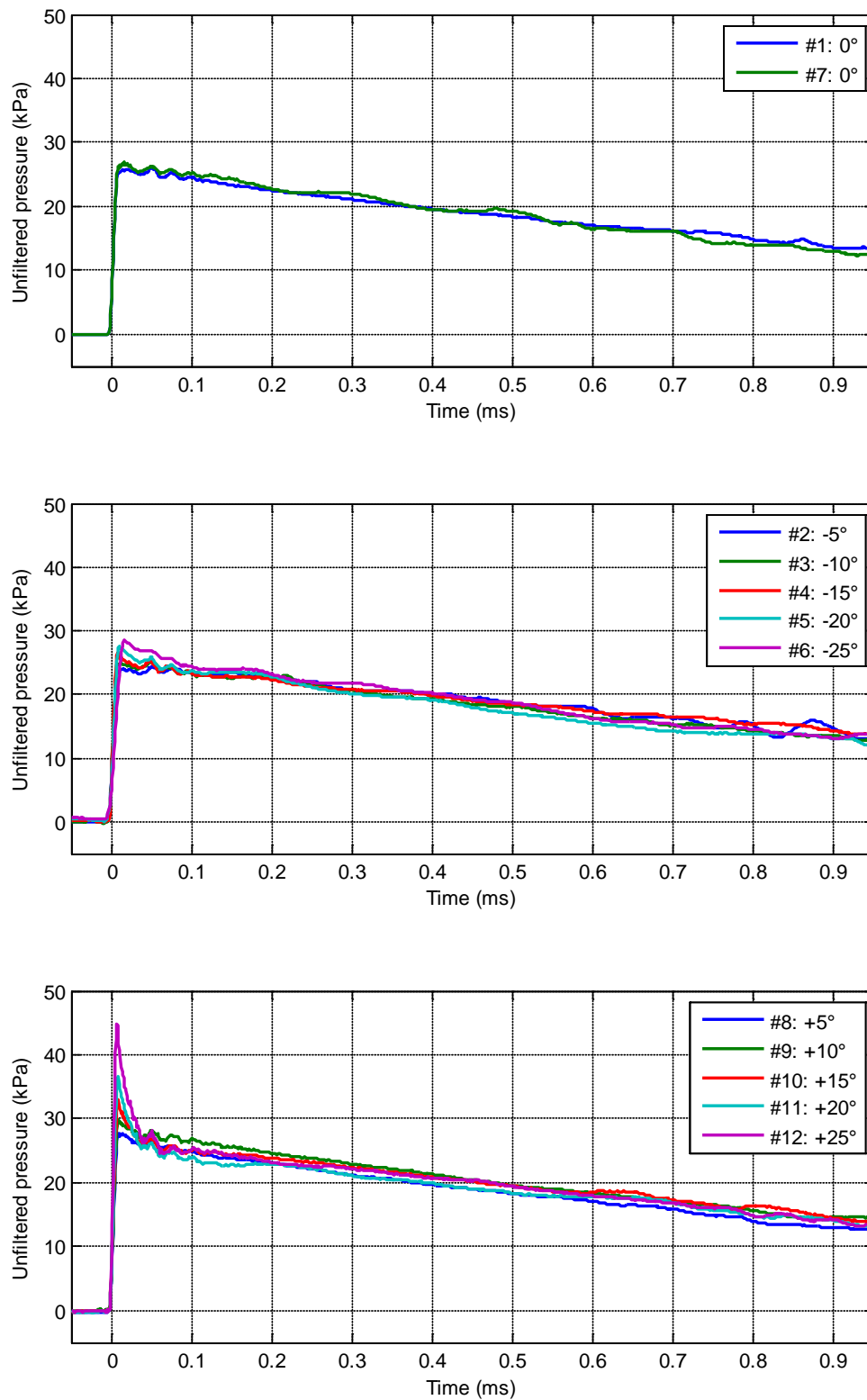
A.2 R2 – 500 g C4
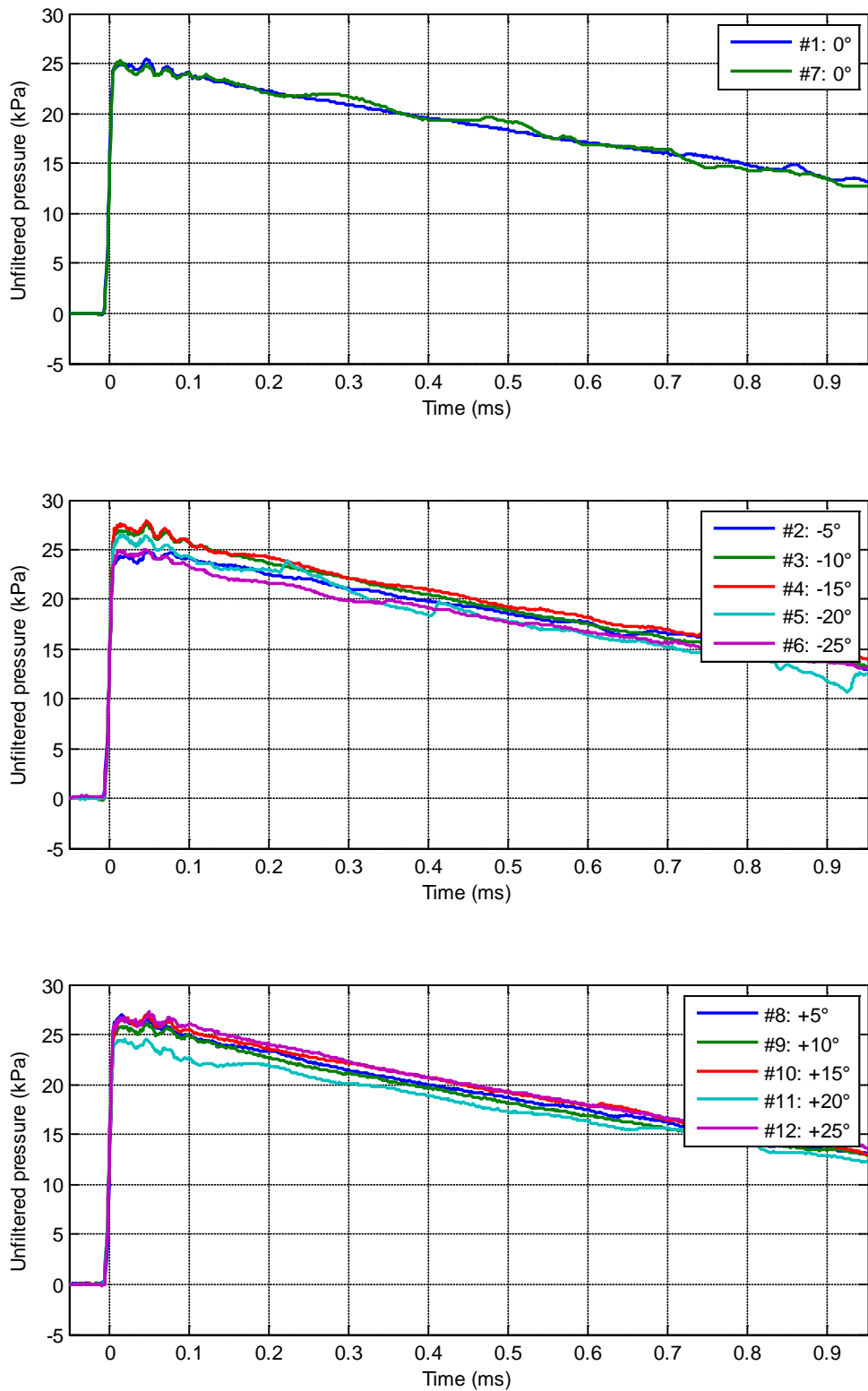
Figure A.3   Unfiltered data.
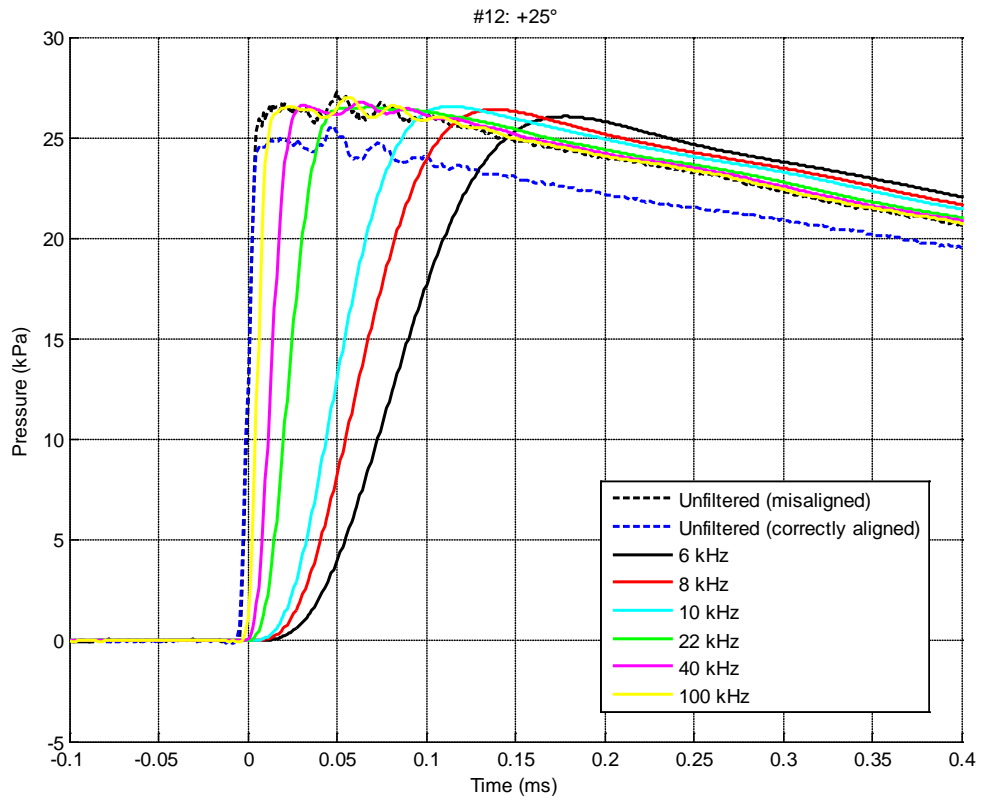
Figure A.4   Pressure-time history plot from pencil probe misaligned at +25°. Filtered data, using varying cut-off frequencies, are compared to unfiltered data and unfiltered data from a correctly aligned pencil probe. Note that the correctly aligned pencil probe seems to overall yield lower pressure-time data than the +25° misaligned pencil probe.

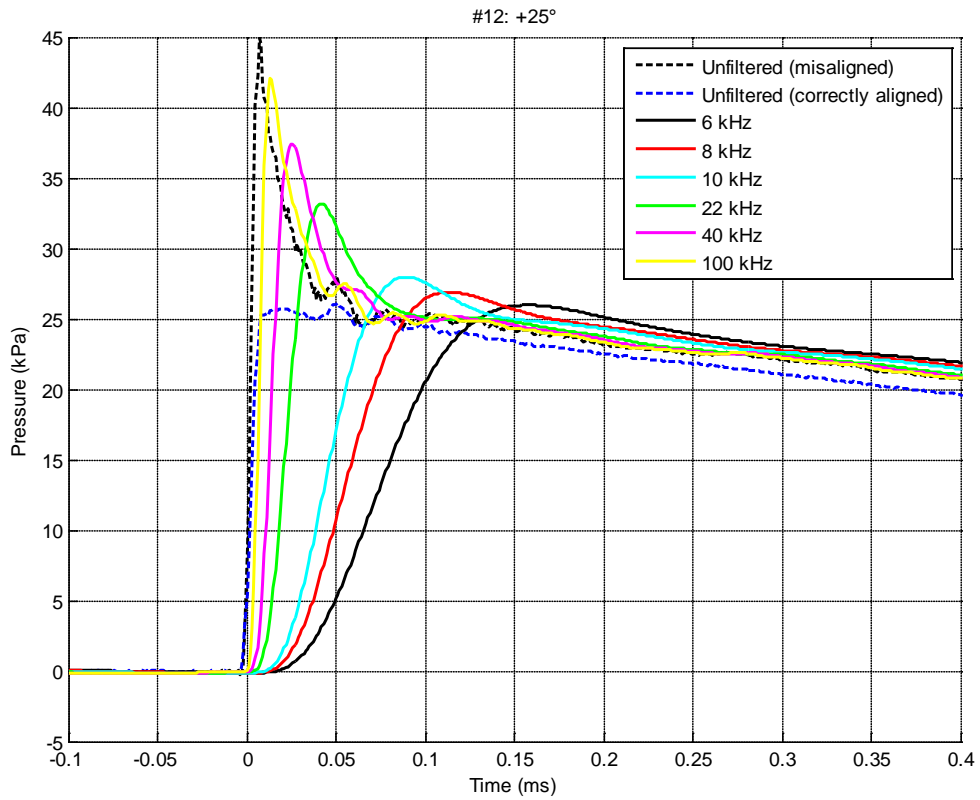## A.3   M1 – 100 g C4
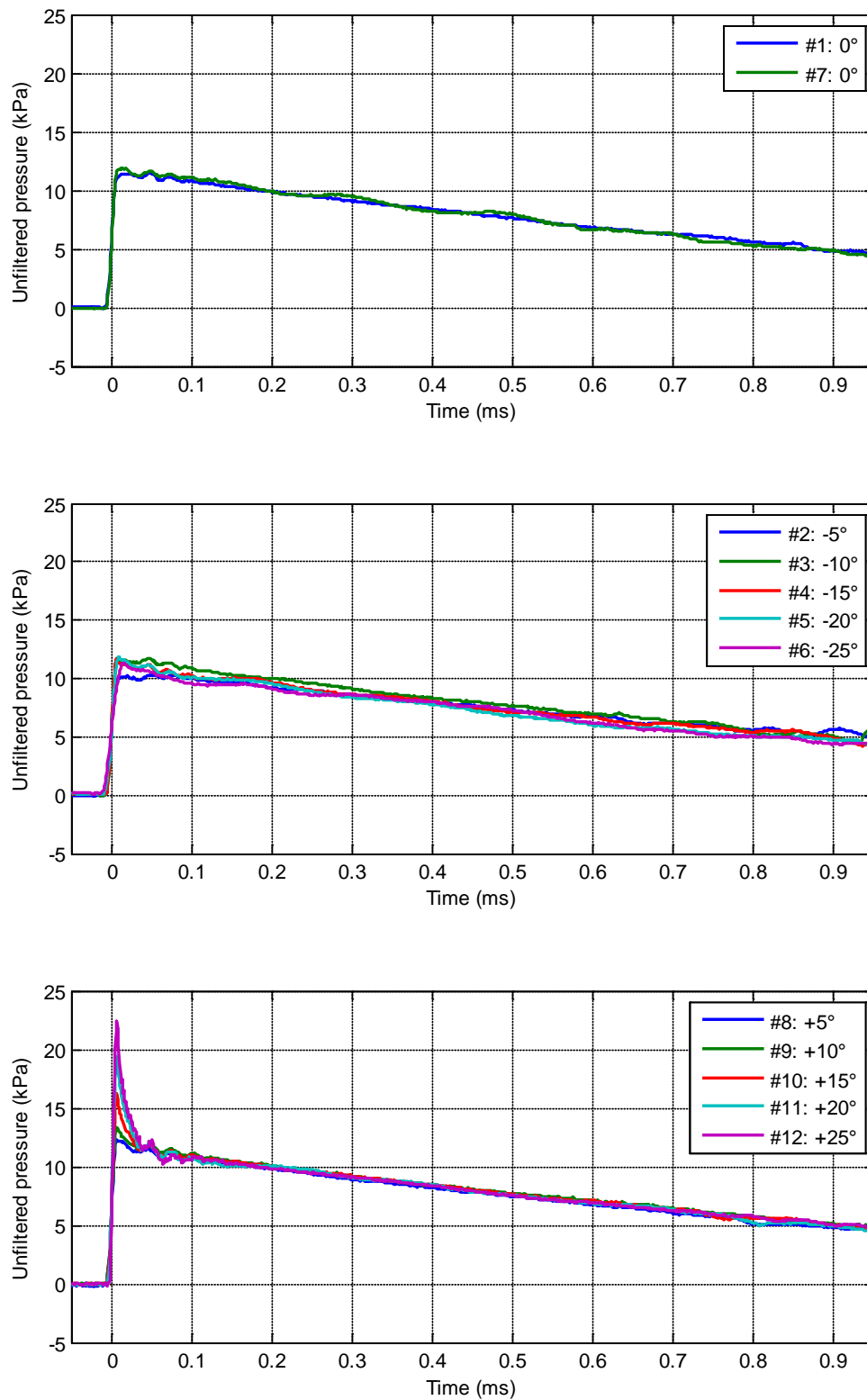
Figure A.5   Unfiltered data.
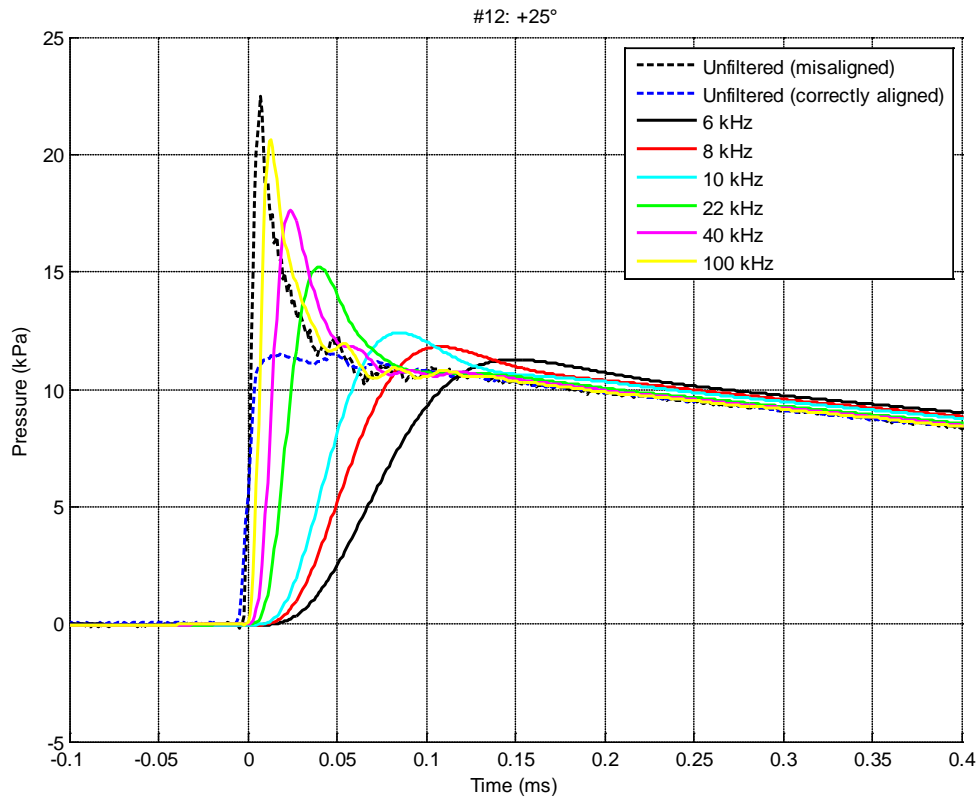
*Figure A.6   Pressure-time history plot from pencil probe misaligned at +25°. Filtered data,
using varying cut-off frequencies, are compared to unfiltered data and unfiltered
data from a correctly aligned pencil probe. Note that the correctly aligned pencil
probe is in good agreement with the +25° misaligned pencil probe, except from the
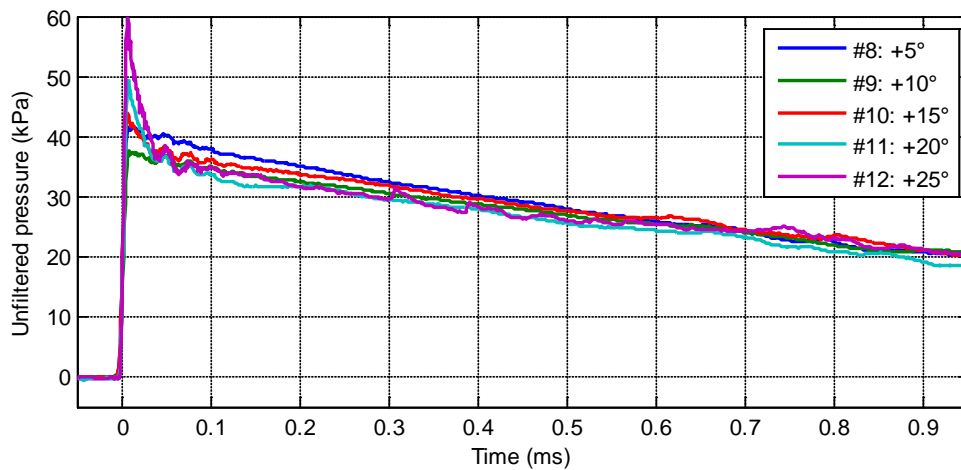first peak.*

A.4 M2 – 250 g C4

Figure A.7   Unfiltered data.

Figure A.8   Pressure-time history plot from pencil probe misaligned at +25°. Filtered data, using varying cut-off frequencies, are compared to unfiltered data and unfiltered data from a correctly aligned pencil probe. Note that the correctly aligned pencil probe is in good agreement with the +25° misaligned pencil probe, except from the first peak.
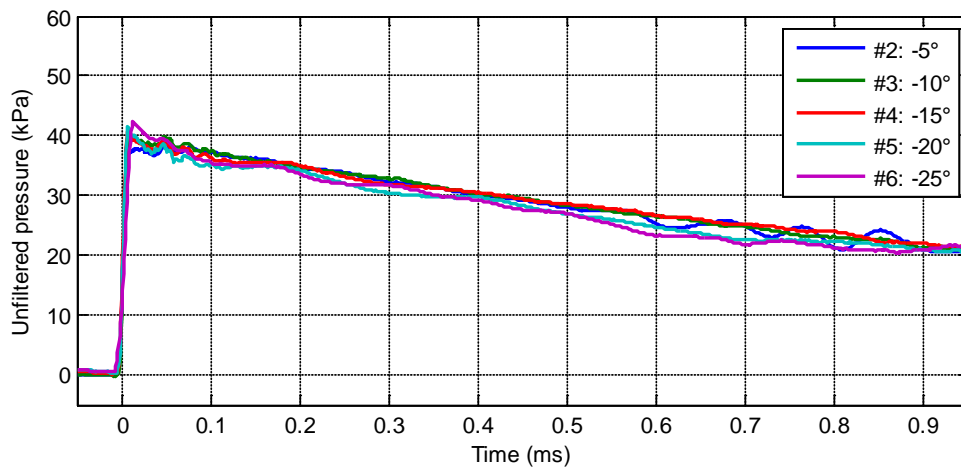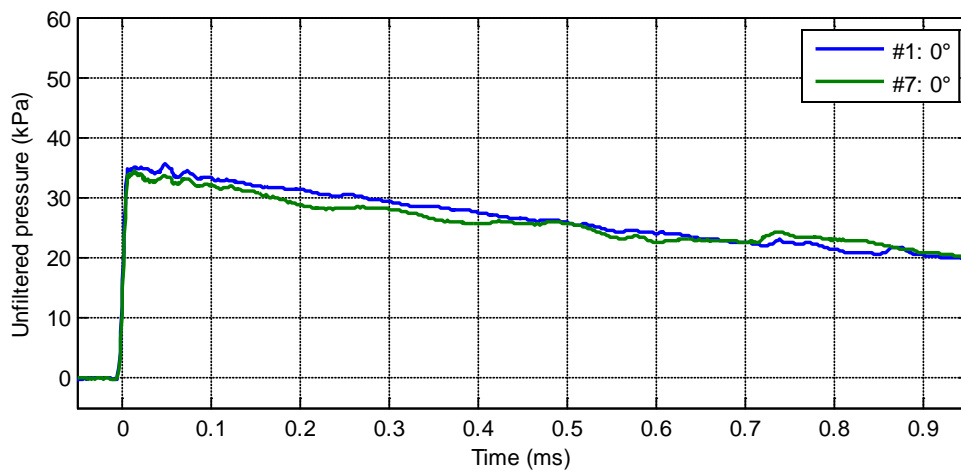
A.5   M3 – 500 g C4

Figure A.9   Unfiltered data.

Figure A.10 Pressure-time history plot from pencil probe misaligned at +25°. Filtered data, using varying cut-off frequencies, are compared to unfiltered data and unfiltered data from a correctly aligned pencil probe. Note that the correctly aligned pencil probe is in good agreement with the +25° misaligned pencil probe, except from the first peak.

A.6   M4 – 1000 g C4

Figure A.11 Unfiltered data. There is possible an error in channel #10. This is based on an expected increase in peak pressure due to misalignment which seems to be absent. However from the visual inspection of the pressure-time history alone, this is not clear.
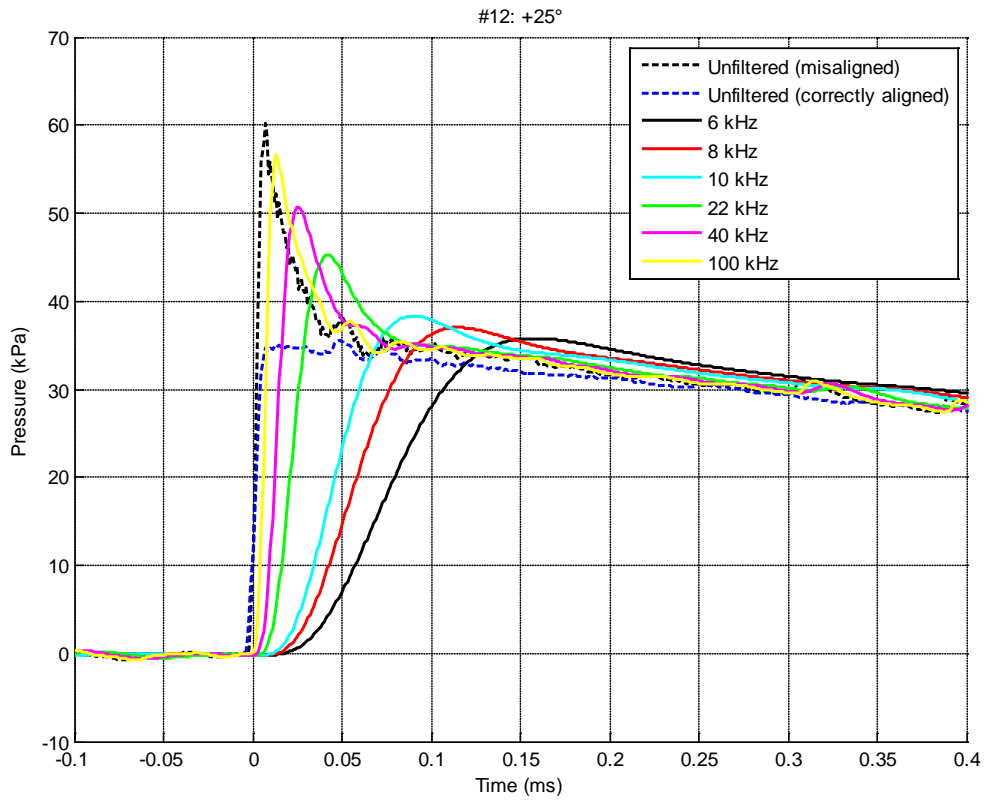
Figure A.12 Pressure-time history plot from pencil probe misaligned at +25°. Filtered data, using varying cut-off frequencies, are compared to unfiltered data and unfiltered data from a correctly aligned pencil probe. Note that the correctly aligned pencil probe is in good agreement with the +25° misaligned pencil probe, except from the first peak.
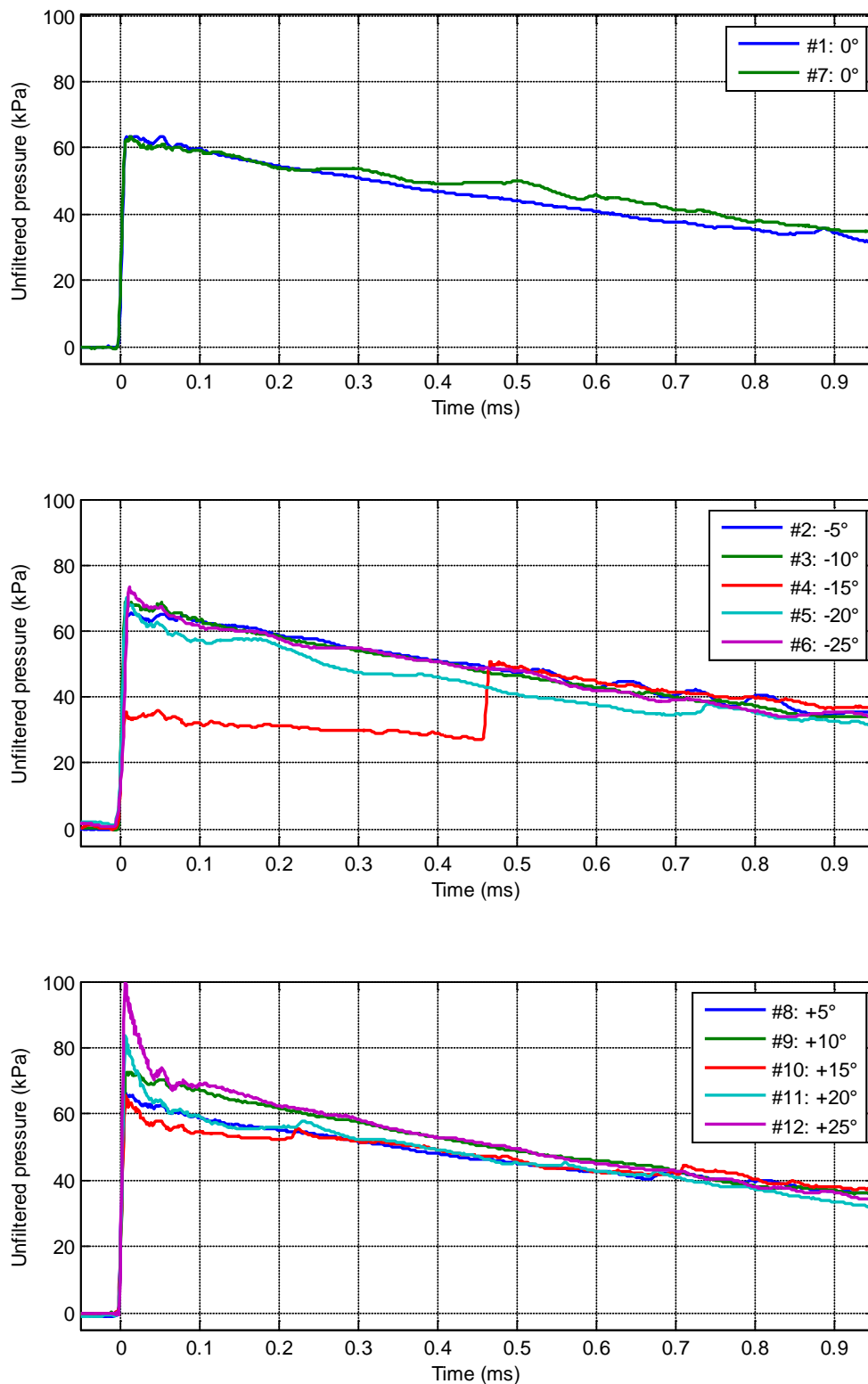
A.7   M5 – 2500 g C4

Figure A.13 *Unfiltered data. Note there is an obvious error in channel #4 in this shot. There is also a possible error in channel #10. This is based on an expected increase in peak pressure which seems to be absent. However from the visual inspection of the pressure-time history alone, this is not clear.*
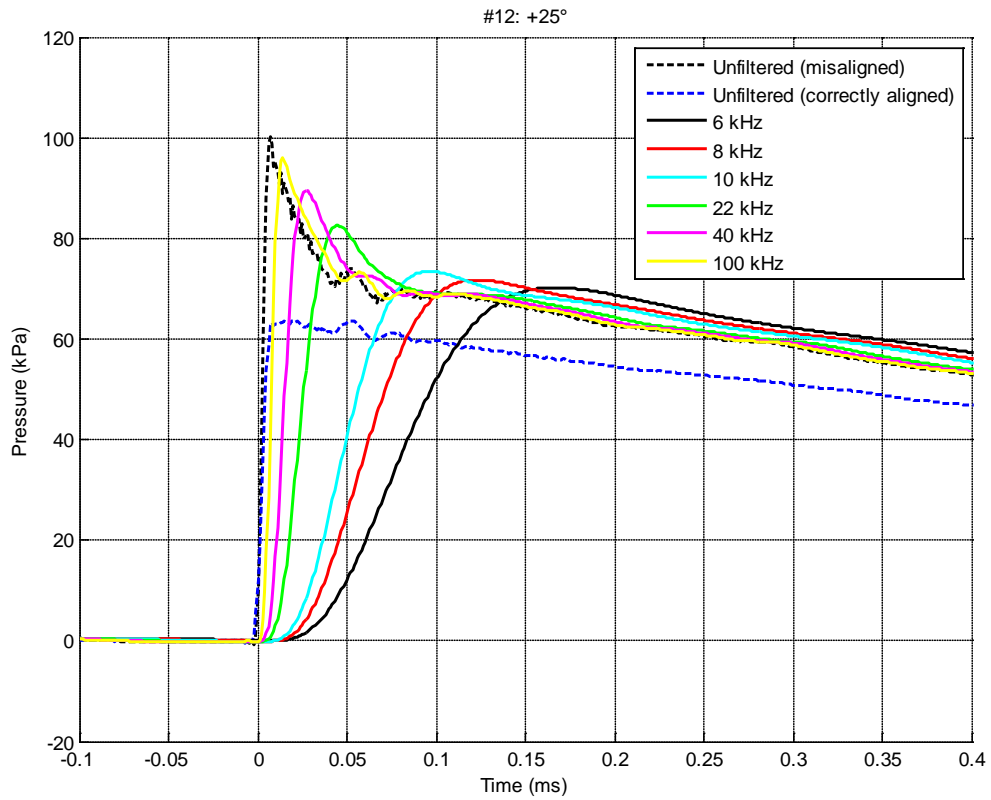
Figure A.14 Pressure-time history plot from pencil probe misaligned at +25°. Filtered data, using varying cut-off frequencies, are compared to unfiltered data and unfiltered data from a correctly aligned pencil probe. Note that the correctly aligned pencil probe seems to overall yield lower pressure-time data than the +25° misaligned pencil probe.
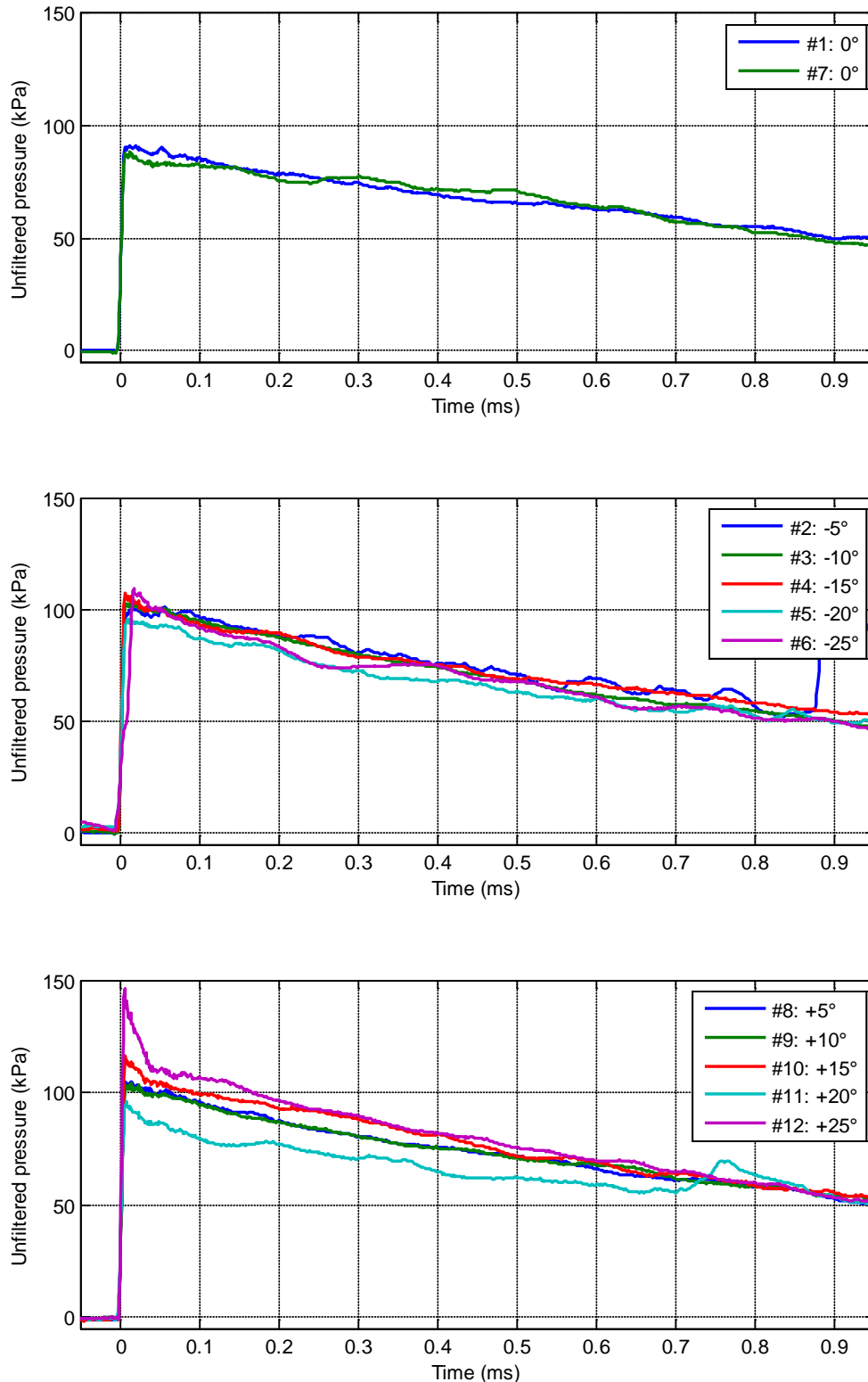
A.8   M6 – 5000 g C4

Figure A.15 Unfiltered data. There is possible an error in channel # 5 and 11. This is based on an expected increase in peak pressure due to misalignment which seems to be absent and due to a overall lower pressure-time history curve compared to the others. However from the visual inspection of the pressure-time history alone, this is not clear.
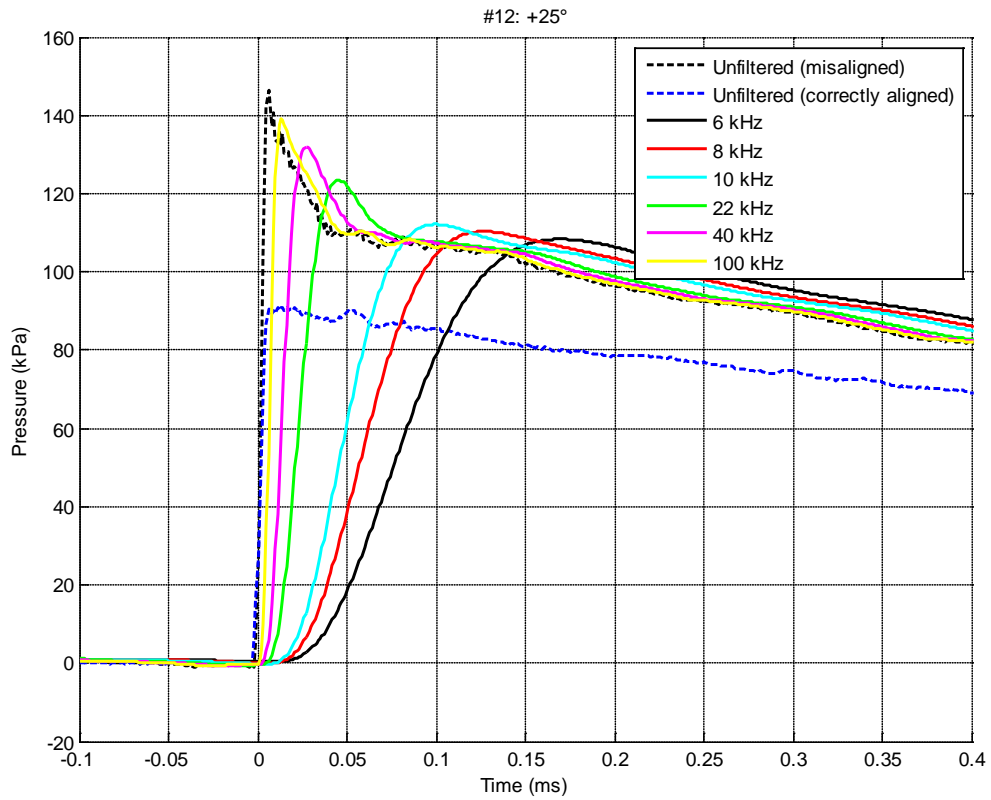
Figure A.16 Pressure-time history plot from pencil probe misaligned at +25°. Filtered data, using varying cut-off frequencies, are compared to unfiltered data and unfiltered data from a correctly aligned pencil probe. Note that the correctly aligned pencil probe seems to overall yield lower pressure-time data than the +25° misaligned pencil probe.