AC jonströmsinterface

AC Ion Current Interface

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Examensarbete
Degree Project
Elektro- och datoringenjörsprogrammet

vt 2008

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Detta examensarbete omfattar 22,5 hp och ingår i Elektro- och datoringenjörsprogrammet, 180/240 hp, vid Karlstads universitet.
This 22.5 hp Degree Project is part of the 3 year, 180/240 point Electrical Engineering course at Karlstad University, Sweden
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Rapporten godkänd,

 datum     Handledare: Peter Röjder

Examinator: Peter Röjder
Abstract
An effective way to extract combustion parameters from a spark ignited engine is to measure the level of ionization. One way to do this is to use the spark plug as a sensor.

Until now this has been achieved by applying a DC voltage over the spark gap which causes an electrical field. The electrical field together with the ionization process gives cause to an ion current which can be measured and analyzed. Previous research suggests that it would be beneficial to replace the DC voltage with an AC voltage.

The focus in this thesis is on the hardware and how to best implement an AC voltage to the existing ion sensing system. Both simulation- and hardware models will be constructed. These models will be tested and analyzed to evaluate both benefits and drawbacks of an AC ion current sensing system.
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1. Introduction
Modern engines are designed to be as efficient as possible. To achieve this, a lot of information about the combustion process is needed and one way to do this is to measure the level of ionization.

Since the combustion chamber is a very harsh environment it is very difficult to make sensors that are both cheap and durable for this task. Instead of using conventional sensors the spark plug can be used as a sensor. This is achieved by applying an electric field over the spark gap, this electric field attracts the electrons that are freed in the ionization process. This causes a flow of electrons i.e. a current that is proportional to the ionization level. By analyzing the ionization process the needed information about the combustion process can be extracted. This technique is called ion current sensing and has been proven to be advantageous.

The purpose of this thesis is to develop a system for AC ion current sensing where the conventional DC bias voltage is replaced by an AC bias. The objective is to evaluate function and possible advantages of an AC ion sensing system with the focus on hardware design. The construction will be based on an existing DC ion current sensing system developed by Hoerbiger Control Systems AB.

The initial validation was done by constructing a Spice model that was used for simulations. These simulations were evaluated for different solutions and methods. When a suitable solution was established and evaluated a hardware version was constructed.

1.1 Combustion engines
Almost all of us are in contact with some sort of combustion engine on a daily basis. The most commonly used combustion engine is the four-stroke spark ignited engine, also called the Otto engine, which is used in most modern car models. Just as the name suggests the engines operation is based upon four strokes, see figure 1.1 [1].

Figure 1.1: Basic figure over the strokes in a four-stroke engine.

- First we have the intake stroke. During this stroke the intake valve opens and a mixture of fuel and air is drawn into the combustion chamber.
• After the piston reaches BDC\(^*\) the intake valve is closed and the piston moves upward. This causes the fuel/air mixture to compress and this is called the compress stroke.
• When the piston approaches TDC\(^**\) a high voltage is applied over the spark gap which introduces a spark to the compressed fuel/air mixture. This causes an explosion that presses the piston downward. This is called the combustion stroke.
• Last is the exhaust stroke that begins after the piston reaches BDC for the second time. The exhaust valve opens to let the piston force out the burned gases.

For an engine to run properly many criteria need to be fulfilled but one of the most important is correct timing of the spark. A spark that is applied to early causes knock that is harmful to the engine. If the spark is applied to late the engine will lose power and efficiency. For correct timing and fuel/air mixture some sort of feedback is required either via conventional sensors or by using the technique discussed in section 1.2 ion current sensing.

1.2 Ion current sensing
To understand the ion current sensing system, one first needs to understand the basics of ionization. When the fuel/air mixture is burning it causes the atoms to ionize, i.e. they release some of their electrons. The amount of free electrons can be measured by applying a voltage over the spark gap. This voltage causes an electrical field that together with the ionization process results in a current which can be measured and analyzed. This current is proportional to the level of ionization, hence the name ion current. From this current you can extract information about among other things timing, knock, pre-ignition and misfire [2].

![Figure 1.2: Basic structure of an ion sensing system.](image)

Figure 1.2 [3] shows an ion sensing system in its most basic form, most modern systems are much more complex. In this system the spark current is used to generate the bias voltage so no external voltage source is needed. During the spark event the capacitor, C1, is charged by the spark current. To set the desired bias voltage level a zener diode, D1, with a reverse voltage of 80V is connected in parallel with the capacitor, C1. After the spark event the capacitor, C1, applies a voltage over the spark gap that attracts free electrons and thereby causing the ion current. The ion current is then measured as a voltage drop over the resistor, R1. The zener diode, D2, works as a bypass for the spark current and also as protection for the ion sensing circuit.

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\(^*\) BDC, Bottom Dead Centre is when the piston is positioned closest to the crankshaft.

\(^**\) TDC, Top Dead Centre is when the piston is positioned farthest away from the crankshaft.
Correct setting of the bias voltage is important. If the voltage is too high it can cause plug fouling and if it is too low the electrical field will be too weak to attract a sufficient amount of electrons and thus failing to generate a current for analysis.

A typical, if there is such a thing, ion current can be seen in figure 1.3[4].

![Ionization Current](image)

**Figure 1.3: Ion current signal and time-windows.**

The information that is of interest can only be extracted during the flame-front phase and post-flame phase. This means that the time-window for measurement is limited and dependant on the engine speed. The time-window is approximately 60° where 360° is a full engine revolution. To put this in a perspective 60° corresponds to 5ms time-window at 2000 RPM.
2. Theories and simulations
To evaluate theories and solutions for AC ion current sensing several simulation models were constructed.

2.1 Earlier tests on AC ion current sensing
Previous work and research about AC ion current sensing have been performed and is a good starting point to better understand the task at hand and what kind of results that can be expected.

Earlier tests with AC ion current sensing performed on diesel engines by Magnus Glavmo have shown that the ion current contains different information depending on the direction of the current. If one can measure the current in both directions, more information can be obtained. Therefore it would be advantageous to apply an AC voltage over the spark-gap instead of the currently used DC [5].

In results from similar measurements on an Otto engine the spark plug caused an inhomogenic behavior of the ion current. The theory is that the small centre electrode of the spark plug causes a strongly inhomogenic electrical field, thus also causing an inhomogenic behavior of the ion current. This opposes the theory of a bidirectional ion current and would prevent any further information from being extracted from the ion current. This test suggest that the AC technique is advantageous due to less sensitivity to plug fouling and automatic separation of leakage current and ion current [2].

As can be seen the two reports [2] [5] contradict each other. This difference in results is probably due to difference in motor types and probes. Although they have different results both reports suggest that an AC voltage would be advantageous over a DC voltage.

2.2 Basic design
The first criteria for AC ion sensing would be to obtain a sine shaped AC voltage over the spark gap. By repeatedly connecting/disconnecting the ignition coil low-side to ground in a switching manner one should be able to generate an AC voltage on the secondary side of the ignition coil. This theory originates from switched power supplies that use a similar technique that switches the primary side of a transformer to generate an AC voltage. The ignition coil can be seen as a transformer and this technique should therefore also work in this application. This method would be beneficial since you do not need to use any separate power supplies to generate the AC voltage. The basic principles are illustrated in figure 2.1.

![Figure 2.1: Basic principles of an AC ion sensing system.](image-url)
The generated AC voltage acts as a carrier that is modulated by the ion current. To extract the information from the signal it has to be demodulated by the ion current interface. In this case the switching is performed by an IGBT\(^*\) that is controlled by the ignition controller. To avoid extra components it would, if possible, be beneficial to use the same IGBT that is used for ignition control.

Timing of the oscillation is of importance because if it starts too early it may cause the spark to die prematurely which would affect the combustion process and if it is too late the window for measuring will pass and less or no data about the combustion process will be acquired.

### 2.3 Simulation
To verify the theories behind the basic design a model of the AC system was designed using Altium designer 6, figure 2.2. For simulation of the ignition coil a model from M. Johansson’s thesis “Ion current interface” [4] was used due to lack of tunable parameters in standard PSpice models. The spark plug model was designed with help from theories presented by H. Wilstermann [2].

![Simulation model of an AC ion sensing system.](image)

Figure 2.2: Simulation model of an AC ion sensing system.

The model can be divided into four parts:

- **Ignition coil**, this part is represented by \( R_1, R_2, R_m, L_1, L_2, L_m \) and \( E_1 \). This is a simple model of an ignition coil but good enough for these simulations.

- **Ignition control**, this part consists of \( V_1, V_2, D_4, D_5, R_6, C_{prim} \) and \( Q_1 \). To simulate the ignition controller two voltage sources are used to control the transistor that switches the primary side of the ignition coil. \( V_2 \) controls the ignition cycle and \( V_1 \) controls the oscillation. \( C_{prim} \) is used to adjust the resonant frequency on primary side of the ignition coil.

- **Spark plug**, this part is represented \( D_{gap}, D_{gap2}, R_{shunt}, R_{rid} \) and \( C_{sp} \). The zener diodes represent the spark discharge. \( R_{shunt} \) represents the leakage current caused by soot and other contaminations. \( C_{sp} \) represents the capacitive part in the spark plug and \( R_{rid} \) is the radio damping resistor inside the spark plug [2].

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\(^*\) IGBT, Insulated Gate Bipolar Transistor is a transistor that behaves as a FET (Field Effect Transistor) on the gate and as a bipolar transistor on the collector and emitter.
Symmetrical ion current interface, this part consists of D_1, D_2, C_1, R_4, R_5, and U_1. This is the first level in the ion current interface and is basically a current to voltage converter. D_1 and D_2 helps the OP\(^*\) keep up the virtual ground during the spark event [4]. To minimize noise C_1 leads frequencies above the desired to ground.

Since the purpose of this simulation is to confirm functionality only, component values might differ from a later realized version.

For the simulations an appropriate switching frequency needs to be decided. Since it acts as a carrier for the ion current signal the minimum carrier frequency is set by the Nyquist rate, \( f_0 \geq 2 \cdot f_{\text{max}} \), where \( f_0 \) is the switching frequency and \( f_{\text{max}} \) is the maximum frequency component of the ion current. The ion current signal can be expected to contain frequencies up to about 10kHz which gives a minimum carrier frequency of 20kHz. To confirm that the construction also works with higher frequencies the switching frequency is set to 60kHz in this simulation. During this simulation the dwell time is set to 2.0ms and the AC generation starts after the spark event has passed at about 2.3ms. For better resolution the ignition phase has been left out of the figure, the complete results are available in appendix 1.

Figure 2.3: Simulation results, from top to bottom, output voltage, gap voltage, ignition control and primary side current.

As can be seen in figure 2.3 the simulation confirms that the theories behind the basic design idea can be used to generate an AC voltage. It can also be seen that it takes a few periods for the amplitude to stabilize which can, but probably not, cause problems due to the limited time window for ion current measuring.

\(^*\) OP, Operational amplifier. In this case it is used as a current to voltage converter.
3. Measurement and validation
The next step in the process is to realize a hardware prototype in a laboratory environment.

3.1 Prototypes
The first prototype was built using an existing coil driver and kept as simple as possible just to confirm basic functionality.

The switching is performed by the coil driver that is controlled by a signal generator. In this first test the current to voltage converter is replaced by a measure resistance. Furthermore these first tests were performed without a spark and the spark plug is replaced by a high voltage resistor in parallel with a high voltage capacitor. To ensure the safety of the coil and keep the voltages down on the secondary side a current limiting resistor, Rlimit, was mounted in the primary current path. Also two zener diodes were mounted to protect the measuring equipment. The complete schematic can be seen in figure 3.1.

![Figure 3.1: Schematic of the first prototype.](image)

This test confirmed what had already been shown in earlier simulations. As could be expected some small distortions appeared on the output signal. Since the objective of this test was to confirm the basic theories results were satisfying enough to continue with further tests and implement the symmetric interface, see figure 3.2.

![Figure 3.2: Schematic of improved prototype with the symmetric interface.](image)
The prototype with the symmetric interface is quite similar to the earlier version but in this prototype a current to voltage converter and two diodes has been introduced. The current limit resistor has also been removed as this would prevent the idea of using the same IGBT for both dwell control and AC generation.

Initially during this test the output signal displayed strong distortions but after some troubleshooting it became apparent that this was due to interference on the OP amplifier supply voltage. The interference originates from the coil and is a part of its reaction to the switching. This was solved with decoupling capacitors on the supply lines. Also some adjusting of the current to voltage converter gain was needed to achieve a non distorted output signal.

These results showed that it is possible to use the AC technique together with the currently used symmetric interface used for DC ion current sensing. This is a major advantage as no new interface needs to be constructed. It was also shown that it is possible to use the same IGBT as for dwell control.

### 3.2 Optimization

For the best possible result switching should be performed as close to the systems resonant frequency as possible. Switching performed closer to the resonant frequency gives a larger ion current and is therefore also easier to extract information from. If the frequency does not match the resonant frequency of the system the resulting output signal may become distorted which further complicates extraction of the information. Ideally the switching should only help the system to keep up the oscillations, rather than creating them.

Since the resonant frequency and therefore also the optimal switching frequency is dependent of the total capacitance, measurements were made to evaluate the impact of variations in spark- and primary capacitance. To evaluate optimal switching frequencies one pulse was applied by the coil driver. This generates a current on the primary side that when interrupted causes a high voltage response on the secondary side, which rings out at the circuit’s resonant frequency. These frequencies where analyzed and documented for selected capacitive loads, see figure 3.3.

![Figure 3.3: Optimal switching frequencies with various capacitive loads.](image)

**Components:**
- Delphi 1900 5240
- Ignition coil

**Equipment:**
- Yokogawa DL9140L
- Digital oscilloscope
- Agilent 33120A
- Arbitrary waveform generator
Because of the relatively small spark plug capacitance the impact on the optimal switching frequency is minimal. The greater primary capacitance has a greater impact on the frequency, this gives the possibility to some extent choose a desired switching frequency by changing the primary capacitance.

Duty cycle is also a factor when generating a sine wave, longer duty cycle gives a larger output voltage but generates larger transients which can lead to a distorted output signal. So unless particular reasons requires otherwise shorter duty cycles are preferred.

3.3 Spark test
To further confirm functionality of the system, tests with a complete cycle with spark were performed. To facilitate the test procedure the coil driver was implemented on the same board as the ion current interface and replaces the previously used external coil driver. To run this test the previously used load had to be replaced by a spark plug, furthermore a longer pulse, about 1.2ms, was applied to the transistor to generate a larger primary current which leads to a higher secondary voltage peak that will set off a spark over the spark gap. After the spark event the switching will be performed as before to generate the AC ion current sensing voltage.

Before a spark was introduced it had to be confirmed that the system was capable of generating a sine wave over a real spark gap. So a pre-spark test was performed where the previously used resistive/capacitive load was replaced by a spark plug but no spark was introduced.

IGBT gate voltage and resulting output voltage during pre-spark test can be seen in figure 3.4.

![Figure 3.4: IGBT gate voltage and resulting output voltage during pre-spark plug test.](image)

As can be seen there were no problem in generating a sine-wave over the spark gap. With this confirmed the spark event was introduced.
Input signal, resulting output voltage, IGBT-gate voltage and coil primary current can be seen in figure 3.5.

![Figure 3.5: IGBT-gate voltage, coil low side voltage (primary side), coil current (primary side) and resulting output voltage during spark test.](image)

These results are very promising and further verify earlier tests and theories, but to effectively extract information from the ion current correct timing of the switching is necessary. In this test fixed timing was used but due to the short time window for measurement and relatively large variation in combustion and spark event duration a fixed timing could be too imprecise in a real application. Therefore some way of detecting when the spark event has passed might be needed. Applications for this task are already developed and therefore not further discussed in this report.

3.4 Final design
Several improvements and adjustments to component values were made in the final design. To better handle variations in frequency and load a potentiometer was added for adjustment of the current to voltage converter gain, see figure 3.6.
Figure 3.6: *Final design, current to voltage converter.*

The coil driver was improved with better transient protection. Instead of leading transients to ground it is lead to the IGBT gate via a zener diode. This causes the IGBT to “open” and thereby save itself and relieve the zener diode, D1. Also a flywheel diode, D3, was added to minimize interference. The 15V zener diode protects the IGBT and also the other components in connection with the IGBT gate, see figure 3.7.

Figure 3.7: *Final design, coil driver.*

It would also be beneficial to replace the input +12V pull-up that is controlled by a bipolar transistor with a FET controlled push-pull design. This would yield a lower bias current and also a faster responding system. Due to time limitations this improvement was not made.

Furthermore an over-dwell protection would be a wise improvement in the future to protect the ignition coil.
4. Dynamometer tests
To further evaluate the AC ion system tests on a running engine mounted in a dynamometer was performed. The resulting output voltage was logged for later analysis.

4.1 Preparations
A way to synchronize the signal generator used to control the AC ion sensing system with the engine is needed. To do this a converter that converts the old coil driver signal, open collector type, to a logical pulse is used to trig the arbitrary signal generator, see figure 4.1.

![Diagram of trig pulse generator/converter](image)

**Figure 4.1: Trig pulse generator/converter.**

The open collector output is converted to a +5V push-pull output via a hex inverting Schmitt trigger. This design should ensure a good trig signal for the signal generator.

The signal generator had to be reprogrammed with a longer switching sequence to cover the whole measuring window at all selected engine settings. This resulted, unfortunately, in a lower resolution in the signal which can result in a distortion of the output AC voltage.

The final construction was then placed in a metal box for protection from both mechanical shock and electrical interference.

4.2 Equipment
Engine: SAAB 2.3L LTT Ecopower with Selma Stand Alone, B235E
Dwell/Switch control: Intuilink, 32120A
Logging, ion current: Yokogawa, DL9140L
Logging, pressure: AVL, Indie master 670
Power supply +5V: Good Will instruments, GPR-3030
Power supply +12V: Delta elektronika, SM3540-D
Power supply +/-15V: ITT instruments, Ax 323

4.3 Performance
Tests were performed in a dynamometer at Hoerbiger Control Systems AB in Ämål.

Tests were performed on cylinder one which was equipped with the AC ion sensing system, that replaces the original ignition coil and coil driver.

The complete setup can be seen in figure 4.2.
Tests were run at three different settings 0 RPM, 2500 RPM no knock and 2500 RPM with knock. At the 2500 RPM settings the dynamometer was set to about 75kPa load. At this setting the engine can be seen as a pump that operates under 75kPa of pressure.

The first run was made with the system mounted in the engine environment with engine not running. This was made with the intention of acquiring a reference signal with no ion current present and to validate that the system works mounted in an engine environment.

The other settings with a running engine were chosen because they represent typical engine-speeds and load where there normally is no problem to extract the ion current information.

For later analysis the output voltage was logged 60 cycles per engine setting.

4.4 Analysis
Analysis was performed with MATLAB by studying the signals in both time domain and frequency domain.

When studying the signals in time domain it can be seen that some interference has appeared which cause noise in the output signals. It seems that this originate from the lower resolution in the output from the signal generator. Also some noise was added by the oscilloscope during the sampling process. This resides in the compromises made in sample length and frequency. These factors are identical at all engine speeds and should therefore be possible to identify and separate from the ion current information.

Figure 4.3 shows the first logged cycle of each signal in time-domain.
Figure 4.3: Modulated ion current presented in time-domain.

As can be seen in figure 4.3 some modulation of the signals is present. It is however too small to distinguish any eventual ion current from the noise.

Since a comparison between the modulated signals did not reveal any ion current information a demodulation of the signals using the communications block-set in Simulink was attempted but due to noise these attempts failed and did not reveal any useful information.

So a last attempt to retrieve the ion current information was made by analyzing the signal in frequency domain by using FFT. But as with the previous attempts no ion current information is detected. The ion current is either too small for detection or not present, see figure 4.4
Figure 4.4: Modulated ion-current presented in frequency domain.

The FFT analysis is evaluated over all 60 cycles and reveals a DSB-FC AM signal. As can be seen in the figure no new frequency components are present in the two signals that were logged with a running engine. All that has appeared is some low frequency noise in the 2500RMP with no knock signal. This means that also this analyze method fails to extract any valuable ion current data from the modulated signal.

What causes this lack of information is unknown but it can be narrowed down to a few critical factors. One factor may be that the ion current amplitude is too weak in comparison with the introduced noise and distortions. Another factor may be an incorrect choice of switching frequency, if the frequency is too high it will be too fast to attract any electrons. It might also be caused by a too imprecise logging.

Solutions to this are still to be decided. It would, however, be a good idea to remove as much noise and distortions as possible. Since some of the interference originates in a too low resolution in the control signal a better signal generator with better resolution is needed.

MATLAB code can be found in appendix 2.
5. Conclusions
By analyzing all results and data from this thesis several important questions about AC ion current sensing can be answered.

Is AC ion sensing possible?
During dynamometer tests the attempts to extract information from the AC carrier failed. Possible reasons could be the compromises that had to be made in control signal and signal logging but further evaluation of this needs to be performed.

A majority of the tests indicate that AC ion sensing is possible. Simulations confirmed discussed theories and gave valuable indications and suggestions for a hardware design. Prototype tests were successful in generating an AC voltage at various frequencies. They also showed the importance of a correctly adapted system. It has also been shown that it is possible to use the same IGBT that is used in the coil driver.

Is AC ion sensing useful?
Since the dynamometer tests failed and new tests need to be performed a definite conclusion is not possible at this moment. Based upon previous research made, one can draw the conclusion that AC ion current sensing would be profitable. The question whether the benefits from an AC ion sensing are worth the work effort that is needed to achieve a fully working system is still unanswered and needs further evaluation.

How do you achieve a fine ion current signal?
What has been shown is that switching should be performed close to the resonant frequency, because this result in the best possible AC bias and should also produce a larger ion current. If large variations in resonant frequency are expected, some sort of frequency detection might be needed to ensure correct switching frequency.

Since it is beneficial to switch with the same frequency as the resonant frequency, adjustment of the circuit’s resonant frequency is of importance to achieve a flexible system. This is done by adding a capacitor on the primary side of the ignition coil, in parallel with the coil driver. Choice of frequency should be made so that the resonant frequency is at least double the information frequency, according to the Nyquist theorem.

Tests have shown that timing of the switching was not as crucial as previously predicted. Starting the switching to early will not kill the spark and is therefore not a problem.

What needs to be improved?
First the bipolar pull-up need to be replaced by a FET controlled push-pull input. A good idea would be to also add a control for max-dwell to the coil driver for component safety. To solve the distortion issues a better signal generator is needed. Some adjusting to the resonant/switching frequency and evaluation of its impact on the ion current might also be needed.

For better analysis a synchronized logging between ion current output and cylinder pressure would be beneficial. The cylinder pressure should be used as an indication of expected information in the ion current signal, which would simplify the analysis. The value of synchronized logging can not be stressed enough; this is of utter importance for the information extraction.
It would also be a good idea to revise the time-windows for logging. Changes will preferably be performed so that the ignition phase also is logged. This information can be used as a time reference when analyzing the logged data.
6. References
[1] Brigham young university
http://www.physics.byu.edu/


http://delphi.com/manufacturers/auto/powertrain/gas/ignsys/ionized/


Appendix 1: Simulation results

Figure 1: Simulation results for ion current sensing at 60kHz.
Appendix 2: MATLAB code

Plot signals in time-domain.

```matlab
% Load vectors
load('x.mat');                  % Data at 0RPM, Reference
load('y.mat');                  % Data at 2500RPM, 75kPa, no knock
load('z.mat');                  % Data at 2500RPM, 75kPa, knock

% User defined
dt = 5;                         % Cycle length (ms)
L = 1500000;                    % Length of signal
n = 60;                         % No. of logged cycles, change to suit currently used signal

% Calculations
Fs = L/(dt*n)*1000;             % Sampling frequency
T = 1/Fs;                       % Sample time
t = (0:L-1)*T;                  % Time vector

% Plot signal
subplot(3,1,1);plot(t*1000,x)
xlim([0 4])
title('0RPM, reference')
ylabel('Amplitude (Volts)')
xlabel('time (milliseconds)');

subplot(3,1,2);plot(t*1000,y)
xlim([0 4])
title('2500RPM, 75kPa, no knock')
ylabel('Amplitude (Volts)')
xlabel('time (milliseconds)');

subplot(3,1,3);plot(t*1000,z)
xlim([0 4])
title('2500RPM, 75kPa, knock')
ylabel('Amplitude (Volts)')
xlabel('time (milliseconds)');
```
FFT analysis and plot signals in frequency-domain.

% Load vectors
load('x.mat'); % Data at 0RPM, Reference
load('y.mat'); % Data at 2500RPM, 75kPa, no
knock
load('z.mat'); % Data at 2500RPM, 75kPa, knock

% User defined
dt = 5; % Cycle length (ms)
L = 1500000; % Length of signal
n = 60; % No. of logged cycles

% Calculations
Fs = L/(dt*n)*1000; % Sampling frequency
T = 1/Fs; % Sample time
t = (0:L-1)*T; % Time vector
NFFT = 2^nextpow2(L); % Next power of 2 from length of
vector
f = Fs/2*linspace(0,1,NFFT/2); % Create frequency vector

X = fft(x,NFFT)/L; % Fourier analysis of x
Y = fft(y,NFFT)/L; % Fourier analysis of y
Z = fft(z,NFFT)/L; % Fourier analysis of z

% Plot single-sided amplitude spectrum.
subplot(3,1,1);plot(f/1000,2*abs(X(1:NFFT/2)))
xlim([46 50])
ylim([0 6])
title('Single-Sided Amplitude Spectrum, 0RPM, reference')
xlabel('Frequency (kHz)')
ylabel('|X(f)|')

subplot(3,1,2);plot(f/1000,2*abs(Y(1:NFFT/2)))
xlim([46 50])
ylim([0 6])
title('Single-Sided Amplitude Spectrum, 2500RPM, 75kPa, no knock')
xlabel('Frequency (kHz)')
ylabel('|Y(f)|')

subplot(3,1,3);plot(f/1000,2*abs(Z(1:NFFT/2)))
xlim([46 50])
ylim([0 6])
title('Single-Sided Amplitude Spectrum, 2500RPM, 75kPa, knock')
xlabel('Frequency (kHz)')
ylabel('|Z(f)|')