

Evaluating A Closed Loop Control System For High Pressure Pumps

By James W Wren, Application Engineer, Prosig Ltd

Prosig were recently involved in the validation of a closed loop control system for an automotive pump supplier. The customer has a large number of test cells, each test cell has 8 pumps continually on test. Each pump is instrumented with a revolution or tachometer sensor, giving a once per revolution tachometer pulse. Additionally, there are various analogue

transducers on each pump which measure parameters, such as pressure at the pump inlet and outlet.

The hydraulic power is provided by a rotary pump (see figure 1). The type of pump shown is a rotary vane pump (figure 2). The pump is driven by the vehicle engine, usually via a belt. It contains a set of vanes that spin inside an oval chamber.

As the vanes spin, they pull the fluid from the reservoir at atmospheric pressure and force it into the outlet at a much higher pressure. The amount of pressure, and therefore flow,

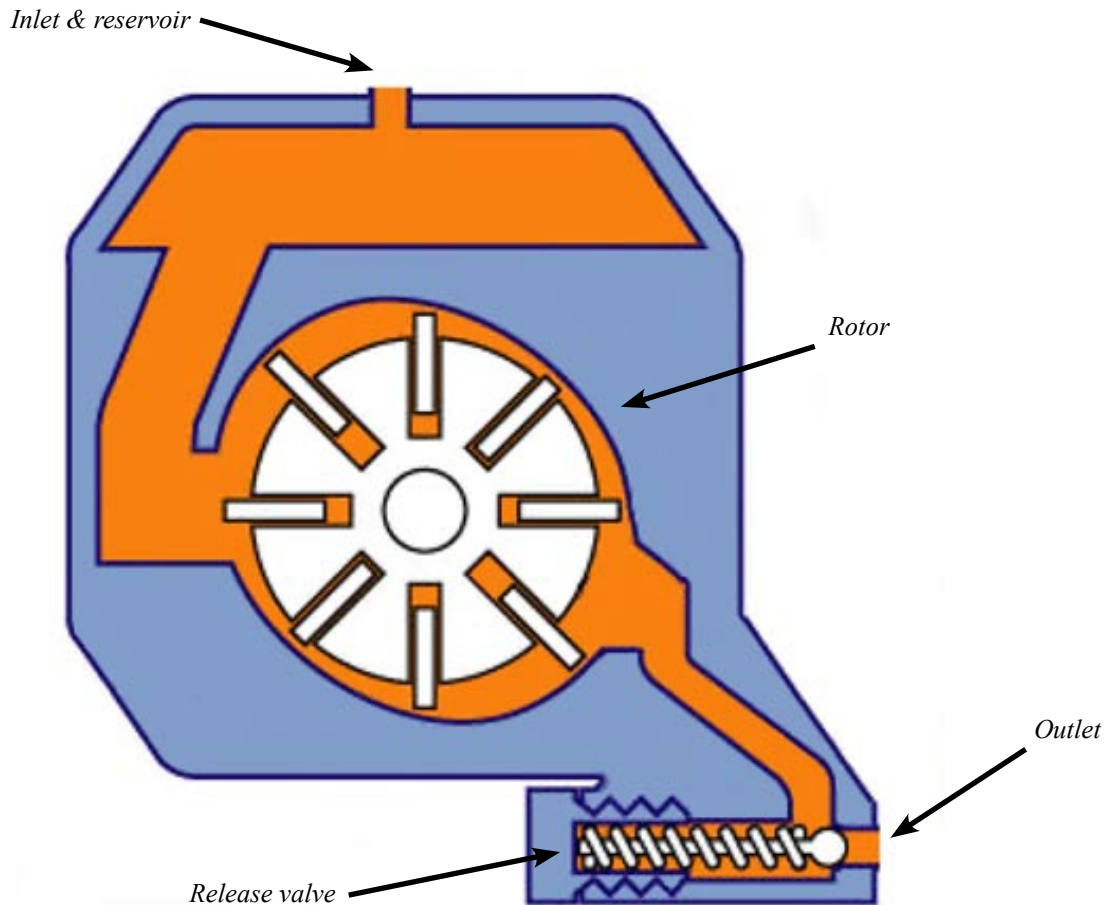


Figure 1: Rotary pump under test

provided by the pump depends on the speed of the pump rotor. Since the pump rotor is driven by the vehicle's engine, its speed is a function of the engine speed. The pump is designed to provide adequate flow when the engine is idling. As a result, the pump moves much more fluid than necessary when the engine is running at higher speeds.

The pump contains a control valve that is electronically controlled and operated. The valve control system ensures that the pressure at the outlet does not move outside a defined tolerance band. If the pressure at the outlet is too low the control valve opens and if the pressure is too high it closes.

The customer needed to validate a newly developed control system. The new system is designed to open and close the release valve a certain number of times for each revolution of the pump rotor. The magnitude and duration of these valve opening events modulates the pressure and flow rate at the outlet to the desired level for the application of the pump.

The Prosig P8000 unit fitted with analogue input channels and tachometer type input channels is used to capture and analyze all the various signals from a pump in one of the test cells.

The function of the pump's electronic control system is to modulate the outlet pressure. To achieve this, the pump release valve has to open and close four times per revolution of the pump rotor. The opening and closing events of the valve should be at very specific times with respect to the pump rotor. That is, for each pump revolution the valve should open and close 4 times. This ensures a steady flow of fluid, but critically allows the pressure to be maintained.

To validate the customer's control system the Prosig P8000 must measure the tachometer channel and the release valve opening and closing. The signals being measured are the tachometer signal and the valve opening and closing. However, the actual value movement is not being measured. As the application is to validate the control system the measured signal

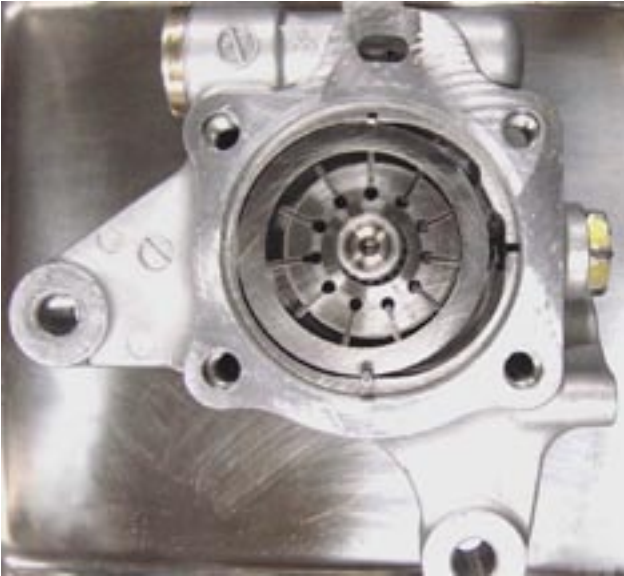


Figure 2: Rotary vane pump

is the electrical signal that energizes the solenoid to open or close the valve. This signal comes from the electronic control system.

These signals must be measured very accurately in the time domain. This is a good way to measure and validate the control system for a particular pump rotor speed, since it is possible to measure the time between the tachometer pulse and the release valve opening and closing. Thus, as the position of the tachometer pulse is known with respect to the position of the pump rotor, this relationship can be deduced. The customer knows what the relationship should be from mathematical calculation and what the relationship is from simulations between the tachometer pulse and the release valve opening and closing.

For the first data capture the pump was driven by the test cell at a speed of 500rpm and the signals captured. The actual relationship between the tachometer pulse and the release valve opening and closing from is shown in figure 3. Figure 3 shows the once per pump rotor revolution tachometer signal. The second signal is the valve control signal, this shows the valve opening

and closing four times for each tachometer pulse. These opening and closing events are for very short durations, as can be seen from the time scale on the graphs.

Figure 4 shows this relationship in more detail. In this case the time between the raising edge of the tachometer pulse and the point of the maximum value opening on the first event is shown using “cursor markers”. The cursor markers are a standard feature of the DATS Professional software. This clearly shows that the time between these events is 15.4 milliseconds.

The two times shown in figure 4 show that, for this particular pump speed of 500rpm, the time difference is 15.4 milliseconds. The customer was able to confirm this was as expected. However, this time relates to an angular difference. The times between tachometer pulses or the time between the pump rotor revolutions must be divided by 360 degrees. The difference in time between the tachometer leading edge and the valve control signal should be multiplied by this factor. The valve is open at some angle after the pump rotor has moved round from its centre position.

So,

$$\text{tachometer raising edge time1} = 0.03346 \text{ seconds}$$

$$\text{tachometer raising edge time2} = 0.15626 \text{ seconds}$$

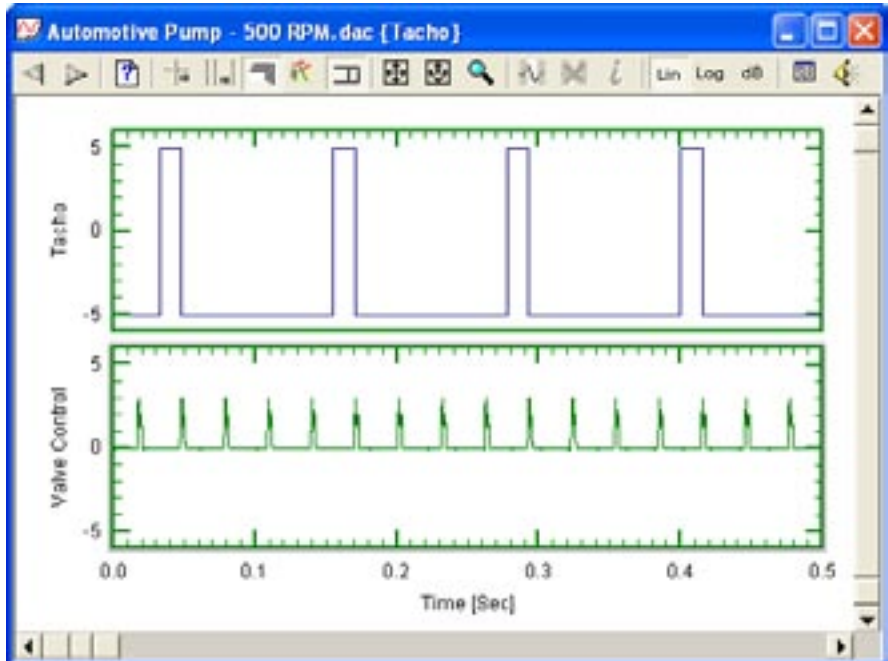


Figure 3: Tachometer and valve control signal

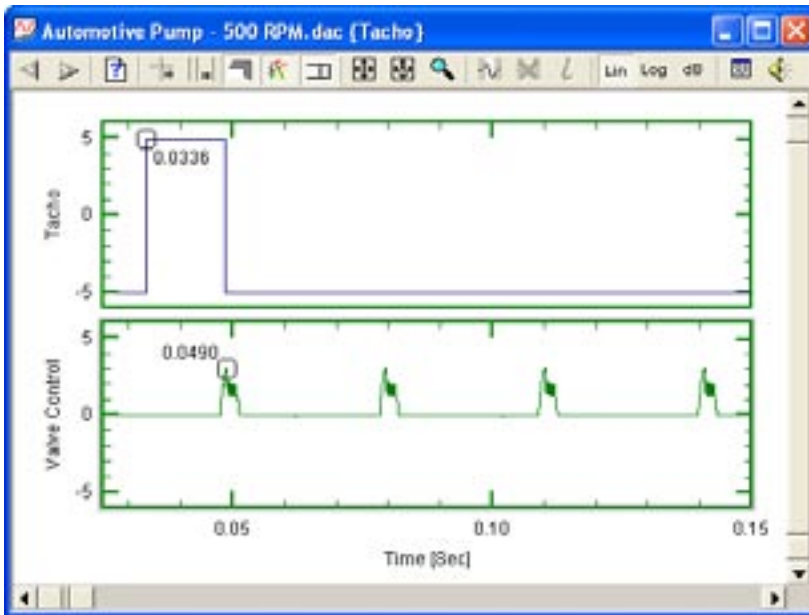


Figure 4: Time difference between tachometer and valve signal

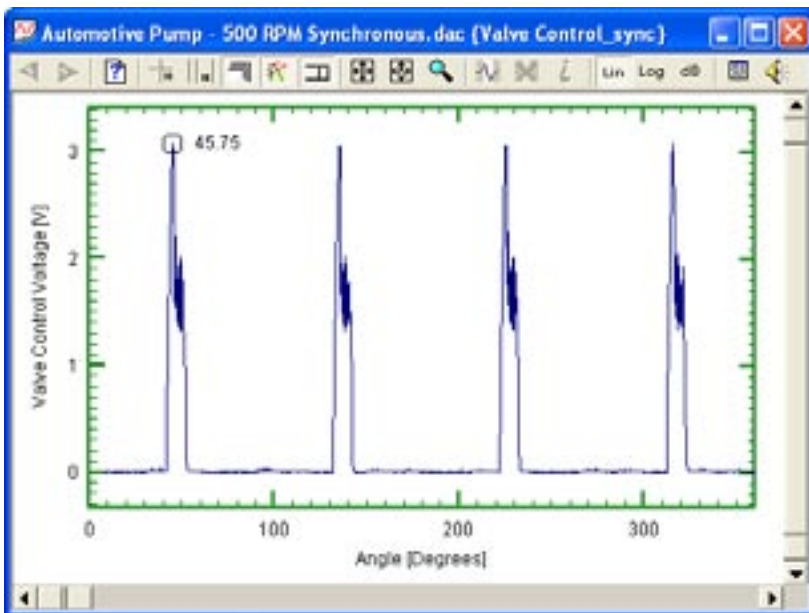


Figure 5: Valve control voltage versus angle

The time between tachometer pulses and therefore a single revolution of the pump rotor;

$$0.15626 - 0.03346 = 0.1228 \text{ seconds}$$

therefore 1 revolution time = 0.1228 seconds

1 revolution time / 360 = time per degree

time per degree;

$$0.1228 / 360 = 3.41 \times 10^{-4} \text{ seconds}$$

Now,

tachometer raising edge time1 = 0.03346 seconds

valve control signal time = 0.04898 seconds

therefore the time between tachometer raising edge and the first valve event is,

$$0.04898 - 0.03346 = 0.01552 \text{ seconds}$$

hence the angular relationship between these two points is ,

$$0.01552 / 3.41 \times 10^{-4} = 45 \text{ degrees}$$

However the customer needed to validate the control system at any speed and not just at a particular speed.

The relationship between the tachometer signal and the release valve opening and closing is not fixed in time. When the pump rotor is moving very quickly the time between the tachometer signal and the release valve opening closing will be very small. When the pump rotor is moving very slowly, the time between the tachometer signal and the release valve opening and closing will be larger.

However, in both cases the relationship between the tachometer signal and the release valve opening and closing four times will be fixed in the angle domain. That is the control system should open and close the release valve four times equally across a single revolution of the pump.

A small complication arises since the control system is actually active, so it will vary the angle very slightly with respect to rotational speed.

However, the customer knows the angular relationship as a function of speed. As stated previously, the test is to validate the control system and make sure it's functioning as expected.

In order to validate the control system the captured

data can be displayed in the angular domain using the DATS Professional software. Figure 5 shows the valve control signal at 500rpm in the angle domain.

Since it is possible to visualize the data in the angle domain, there is no need for the comparison between two signals.

Figure 6 shows the angle at a higher speed - 3500rpm. In this case the maximum peak is more difficult to pick out as it is much faster. The graph clearly shows the maximum point at 47 degrees. The DATS professional software peak detection software is optimized for this sort of complex analysis and detection.

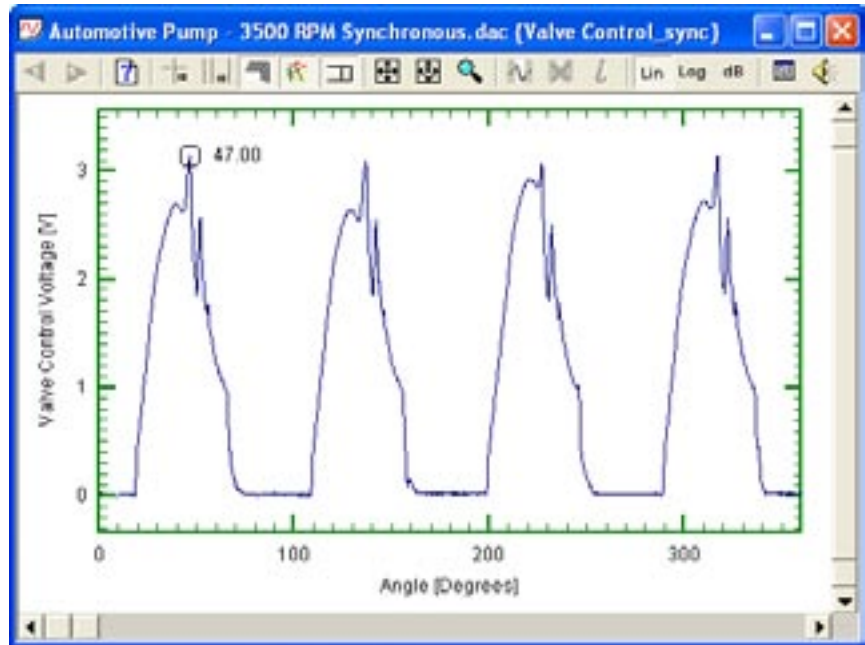


Figure 6: Valve control voltage at 3500rpm

Using our first method, the data is captured and shown in the time domain. The tachometer signal is shown with respect to the valve control.

Using the second method, the data is shown in the angular domain. There is no tachometer signal shown, only the valve control with respect to the tachometer signal.

The first case requires that the sample rate is set so that the highest frequency present is captured and retained. In this case the Nyquist theorem applies. The Nyquist theorem states that the sample rate must be at least twice the bandwidth of interest. Therefore the customer must know the frequencies of interest before the data capture.

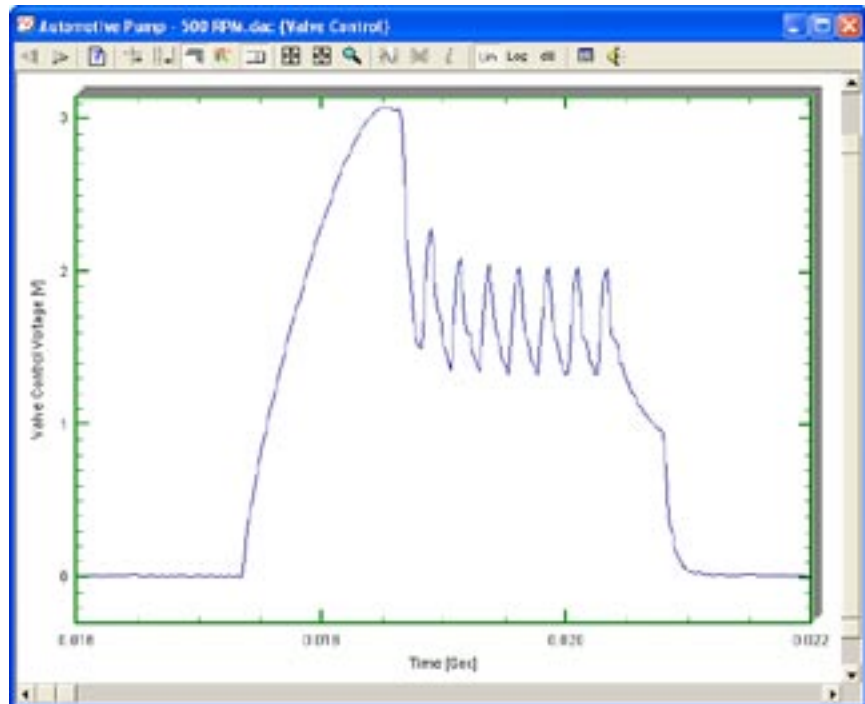


Figure 7: Valve control voltage showing high frequency content

In this case the highest possible pump speed was 4000rpm. The tachometer transducer gives 1 pulse per revolution and therefore the maximum is 4000 pulses per minute. This equates to 67 pulses per second, or 67 Hz. But the Nyquist theorem states that we should sample at least twice this, at 133 samples/second. However, using the value of 133 samples / second for signals like this

could result in serious under sampling. There are three reasons for this.

First, the valve control signal runs at four times this rate. We know this because the valve is opened

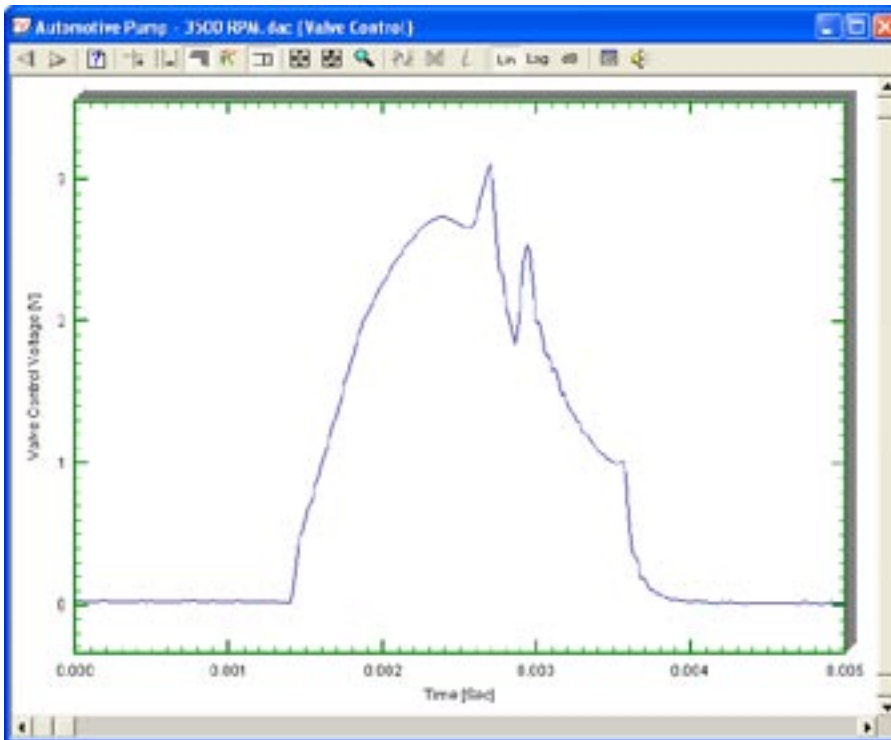


Figure 8: Valve control voltage at higher speed

and closed 4 times per pump rotor revolution. Therefore we should be considering $133 \times 4 = 532$ samples / second.

Secondly, the dynamics of the valve should be considered. As can be seen in figure 7 the valve control signal actually has high frequency content itself. This can be clearly seen between 0.019 seconds and 0.021 seconds.

The length of each of these short impulses is approximately 239 microseconds.

Therefore, the frequency content of these high frequency spikes is related by

$$f = 1 / t$$

therefore

$$f = 1 / 239 \text{ microseconds}$$

$$f = 1 / 239 \times 10^{-6} \text{ seconds}$$

$$f = 4166.67 \text{ Hz}$$

So to safely capture this data we should sample at a minimum of twice this frequency.

Checking the higher speed data captures for the same phenomena reveals, as expected, much higher frequency content (figure 8).

This can be seen between 0.0025 and 0.0031 seconds.

The time of these short impulses is 199 microseconds.

Using the same relationship

$$f = 1 / 199 \times 10^{-6} \text{ seconds}$$

$$f = 5000.0 \text{ Hz}$$

Again at least twice this rate should be used, so now we have a minimum sample rate of 10000 samples / second or 10k samples / second.

Thirdly, we must consider

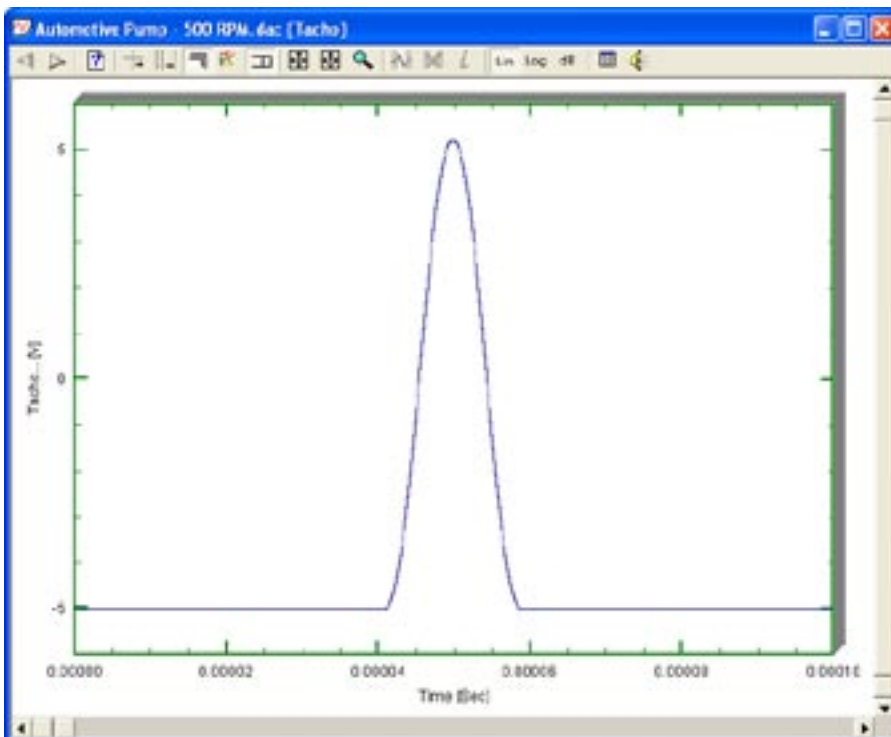


Figure 9: Detail view of tachometer signal

the dynamics of the tachometer signal. Although as discussed the tachometer has a maximum repetition of 67 times per second, this does not give a complete and full picture of the dynamics of the signal. Shown in figure 9 is a tachometer pulse in great detail.

Although this event happens some 67 times per second, the event itself lasts only 20 microseconds.

This means the frequency content of the tachometer pulse is, again using,

$$f = 1/t$$

therefore

$$f = 1/20 \text{ microseconds}$$

$$f = 1/20 \times 10^{-6} \text{ seconds}$$

$$f = 50000.0 \text{ Hz}$$

As previously discussed, to capture this 50000 Hz event a sample rate of at least 100000 samples / second must be used.

Now that the signals are fully understood it is possible to see what sample rates should be used for a test such as this.

The tachometer signal must be sampled at a minimum of 100,000 samples / second.

The valve control signal must be sampled at a minimum of 10,000 samples /second.

The Prosig P8000 supports sample rates of up 800,000 samples / second. Importantly it also samples each channel synchronously. As with all rotating machinery

analysis multiplexed equipment is not acceptable.

Displaying the data in the angular domain, as discussed in the second of the two methods, is more complex. If this sort of display is required then the sample rate of the tachometer channel and valve control signal must be at the same highest rate. In this case, at least 100,000 samples / second. This is to ensure that the angular domain valve control data can be displayed accurately with respect to the tachometer channel in the angle domain.

James Wren



James Wren is Sales Manager and an Application Engineer for Prosig Limited. James graduated from Portsmouth University in 2001, with a Masters degree in Electronic Engineering. He is a member of the Institute of Electronic Engineers. He has been involved with motorsport from a very early age with special interest in data acquisition. James is a founder member of the Dalmeny Racing team.



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Prosig Hardware Used in This Article

- **P8012 - 3 card chassis**
- **Configurable channel options**
- **24-bit accuracy**
- **Up to 12 high speed analog channels**
- **102dB dynamic range**
- **-120dB noise floor**

The P8012 supports 12 high speed analog inputs plus two digital tacho. Units can be stacked to expand the system up to 80 channels. Various input options are available. These include high speed analog, low speed analog, thermocouple, strain gage, high speed tacho, CAN and GPS. Each option is complete with programmable signal conditioning, which is controlled by the DATS™ software.

P8012 Data Acquisition System



Prosig Software Used in This Note

DATS™ Professional software (01-55-622)

- **Acquisition, analysis & reporting**
- **Wide range of analysis functions**
- **Automated processing through worksheets & scripts**
- **Built-in report generator (Intaglio)**
- **Comprehensive QA features**

The DATS software package contains all of the measurement and analysis tools needed in an engineering or research environment. Data acquisition software comes as standard. There is a comprehensive framework of analysis tools (interactive worksheets and scripting). The Intaglio report generator provides template driven, high quality reports.

DATS offers outstanding value both in cost and productivity gains. There are no extra costs for data acquisition support, analysis scripting or reporting software. And you won't pay a fortune for support even though we provide a service agreed by many to be the best available. And if you subscribe to our modestly priced support service you will be entitled to regular software updates.

Many man-years of signal processing expertise have been spent on DATS during its 30 years of development. When you purchase DATS you are buying a share in our knowledge. DATS software has proved itself time and time again in diverse and demanding applications around the world.

DATS is built around a fully published, standard data format. A number of features make the DATS data structure unique:



Graphical interactive and automated capture, analysis & reporting

• A complete history of any analyses performed is stored with every signal. This provides a complete audit trail from data capture to final result.

• The Named Element facility provides for storage of everything from data acquisition settings to results of analyses.

• The integrated Project Manager allows a user to configure and store any variables relevant to a test or project with every signal captured or analyzed for that test. DATS includes a full featured acquisition suite. Capture parameters are easily configured using the setup matrix. During a capture real-time displays show time histories, frequency spectra, numerical levels, gauges, waterfalls and order tracks. Channels can be tagged for immediate analysis and results of this can be viewed immediately after capture. Automatic averaging of multiple runs is included and averaged runs can be easily reviewed and assessed.

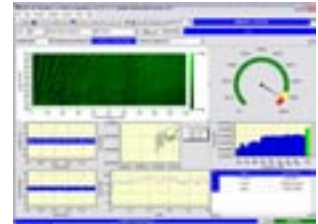
As well as a highly interactive mode, DATS can be automated either using the Visual Scripting environment built into the worksheet interface or using the DATS BASIC scripting language.

Scripts offer a fully featured Visual BASIC® style language. Write your own sequences with data acquisition, input & result forms, DATS analysis functions, reporting, signal access functions, integration with OLE enabled applications (Microsoft® Office etc) and much more.

An important part of most tests or investigations is the final report. DATS includes the Intaglio Report Generator that combines the word processing power of Microsoft® Word and the graphical and analysis capabilities of DATS using OLE technology. Draft reports (templates) are created using Intaglio tools. Each time a report is required the latest data is added to the draft to produce the final report. Reports can be edited by the author, but are "locked" when the report is distributed.



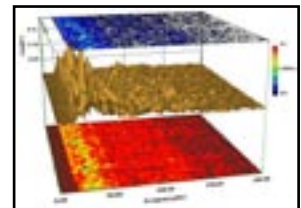
Easy grid based setup for fast, efficient data capture



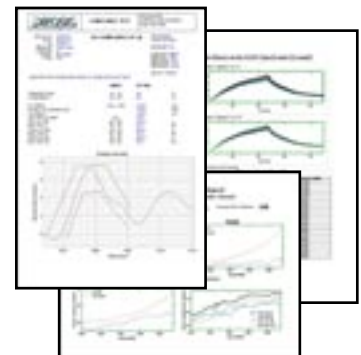
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Results processed by capture software and available immediately following test



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