

# THE INFLUENCE OF INHERENT INJECTOR CHARACTERISTICS ON HIGH SPEED MULTI EVENT, FUEL DELIVERY

David Macdonald

*INOVA Technologies plc*

## ABSTRACT

*In order to meet the demands of higher engine speeds and tighter exhaust emission levels, both direct injection gasoline and diesel injectors are being run at higher rail pressures and where possible with smaller orifices. More complex injection events, at higher speeds, shorten the time between injection events. Since the injector can only at the moment operate as a fully-on, fully-off device, control of fuelling is effected by rapid switching from off to on, with in some cases very short "on" periods, especially to accommodate pilot injection and equally short "off" periods. The injector characteristics and the vibration experienced by the injector significantly influence the hydraulic event timing at higher engine speeds.*

We have described in previous papers some of the observed effects of extremely high exit velocities in injectors, resulting from high line pressures allied to small nozzle apertures. The key benefit seems to relate to the acoustic cracking of the fuel both into its constituent components and the break down of long chain hydrocarbon molecules into simpler units, releasing hydrogen and other lower temperature volatiles. (Figure 1).

This ultrasonic flow creates an effective stratification of the charge, with lighter lower temperature materials close to the injector tip and the higher weight fractions travelling significantly further. The combustion process starts in the area of lighter volatiles and gases and this results in reduced combustion temperatures. A clear understanding of the flow performance of a fuel system is critical in improved engine performance and in meeting emission targets through more accurate mapping with the potential of reducing particulates or unburnt hydrocarbons.

Common rail diesel injection can achieve through orifice droplet velocities of over 4000 metres per second. In so doing, vacuum voids are created within the droplet. The collapse of these vacuum voids induces extremely high vibrational frequencies in the material. (Figure 2). These energy levels are sufficiently high to bring about the breakdown of complex long chain molecules into shorter simpler

fragments, as well as causing fuel mixtures to separate into their constituent fractions.

It is perhaps worth bearing in mind the actual energy levels involved: in water, lower ultra sonic flow velocities give rise to localised temperatures that can exceed 5000 degrees Kelvin.

This acoustic cracking is an essential element of pre-combustion chemistry and allows the higher operating speeds of modern diesel engines. (Figure 3). It is also an essential part of the emissions package since the breakdown of complex long chain hydro-carbons increases the hydrogen content and as a direct result reduces combustion temperatures, limiting NO<sub>x</sub> formation.

Direct injection gasoline systems have to operate at lower pressures because of the lack of inherent lubricity in the gasoline. However, spray velocities of some significance are achieved and the simpler molecular structures of gasoline are more susceptible to acoustic cracking than the heavier and as such more energy absorbent molecules present in diesel fuel.

However, these advantages come at the price of more complex injector behaviour at or close to the edges of the injector's performance envelope. Since even current state-of-the-art injectors can only operate as a fully-on, fully-off device, control of fuelling is effected by

rapid switching from off to on, with in some cases very short “on” periods, especially to accommodate pilot injection. (Figure 4).

The AKRIBIS measurement device has been continuously developed to enable an accurate measurement of hydraulic delivery to be made. For some time, the anomalous delivery rate results that we observed were thought to be possibly a result of the measurement system itself, but as greater levels of accuracy and response have been achieved, the accuracy of the system has been supported. That accuracy is to resolutions of less than 0.003 cubic millimetres with a time base of less than 5 microseconds. (Figure 5).

The AKRIBIS unit differs from other measurement and analysis systems. Although it employs a piston, that piston solely acts as an interface between the injected fluid and the back pressure, giving accurate measurements of quantity against time from which rate curves can be constructed. The system is inherently more accurate than its competitors and, critically and unlike pressure based systems, records changes in the injected fluid that arise as a result of injection. It is these changes, as opposed to the simple flow rates, that are the important information for the engine design team and that provide an effective means of comparison between injectors and fuel systems.

The abnormalities that are observed, especially the fluctuating injector performance and the hydraulic delivery discrepancies experienced at very short time intervals between injection events, are clearly related to injector characteristics. As part of that work we have instrumented our own test beds with comprehensive vibrational analysis facilities enabling us to measure injector and rig accelerations.

We have examined the performance of injectors, both piezo and solenoid operated, and observed continuing disturbance after the notional closing of the injector. That disturbance is not a result of inherent AKRIBIS characteristics: it is of a very different order from the trace created by instrument vibration. (Figure 6).

We have also plotted the accelerations experienced by the injector. By comparing the signal timing, the pintle lift timing, the vertical vibrational characteristic of the injector and the actual hydraulic performance of the injector, a number of conclusions can be drawn.

What appears is that hydraulic delivery is heavily influenced by injector design, both mechanical and electrical. (Figure 7). The electrical performance is, broadly, predictable. It constitutes the operational delays and as such can be factored in to engine mapping. However, at higher engine speeds and consequently shorter durations between two injection events, the variations in electrical performance do become significant.

The mechanical performance of the injector introduces delays, which can become quite pronounced where the actual time interval between pilot injection and main injection becomes very short. (Figure 8).

A number of influences are apparent. The actual opening of the pintle, initiating flow, is influenced by the vibration and resonance of the pintle and solenoid/piezo arrangement. Thus, if the pintle is energised to re-open shortly after closure of, for example, the pilot injection, some degree of further vibration is introduced which affects the initial flow of the main injection event.

Even where the pintle is damped, the interaction of hydraulic flow and pintle movement makes the actual hydraulic performance in the closed interval variable.

More critically, the nozzle itself distorts at the beginning of flow, before hydraulic flow is established through the nozzle orifices. The nozzle extends within the elastic limits of the metal and then contracts once flow has commenced, and continues to vibrate exhibiting a high frequency vibration or oscillation in the nozzle. The damping frequency will depend on materials used, nozzle design and size and on repeatability nozzle to nozzle. As the nozzle distorts, the *vena contracta* moves in the orifices and alters droplet size and fuel changes in the pre-combustion state. (Figure 9).

These changes also alter the spray pattern quite significantly. The use of sophisticated pattern analysis such as phase Doppler laser anemometry cannot capture the droplet velocities and is in any event limited to recognising almost spherical shapes. The high speed pattern from an injector contains comet-shaped droplets and capturing the trajectory and trajectory changes is outside the capacity of optical systems. We believe that it is of essential importance that the actual spray pattern is capable of being resolved and are beginning to investigate systems based on

advanced developments of precision radar to give both trajectory and internal cone characteristics at very high droplet velocities. The ultrasonic flows are complex to model although Dr Kraft and his colleagues including Dr Clemens Kaminski at Cambridge are making considerable progress in this work.

At high engine speeds, where the interval between injection events is very short, the vibrational characteristics of the injector have a relatively unpredictable effect on fuel delivery. The extent to which this affects emissions has prompted INOV8 to invest in engine test stands capable of linking actual engine performance with the hydraulic flow identified on the AKRIBIS test rigs.

The spray pattern and its changes with combustion chamber pressures is crucial in high speed injection. In addition, the pressure environment into which fuel is injected has a major influence on the conditioning of the fuel. This is of particular importance where part of the injection event occurs during a period of high cylinder pressure. Changes in cylinder pressure obviously alter the pressure differential across the injector orifice and this changes the *vena contracta* frequency. The results are considerable alteration in droplet size and conformation. This in turn changes surface area to volume relationships and as a result also alter pre-combustion chemistry.

Whilst this has less adverse effects on diesel engines, it is of great importance in gasoline and in forthcoming homogenous charge CI engines, where line pressures are lower and where the degree to which sono-chemistry can complete necessary pre-combustion changes is far less. If surface area to volume ratios are reduced, the chemistry required for complete, low temperature combustion are harder to achieve. These changes are largely promoted by the activity of free radicals, principally hydroxyl radicals.

Where the time interval between the end of one injection (for example, a pilot) and the start of another (for example, the main) is very short, at high engine speeds, the start of delivery is compromised by the nozzle dimensional changes. Although the actual dimensional change is small, the increase in volume is significant in terms of injection volumes and the vibrational frequency of the nozzle extending and contracting is sufficient to alter the desired injection characteristics.

By comparing the effects on delivery rates of induced vibration and the vibration inherent in an injector, some useful data can be derived. (Figure 10).

It is clear that hydraulic flow can and does continue after the desired cut-off point.

That in turn can mean that the commencement of hydraulic flow of subsequent events also differs from the anticipated point.

The volumes of fuel involved are, obviously, very small and it could be argued of little real importance. However, the key aspect is that the injector performance itself does influence droplet velocity and this is of real importance in the effect that reductions in through orifice velocities have on combustion chemistry. (Figure 11).

Where direct injection gasoline engines are already operating at the limits of pre-combustion chemistry at higher engine speeds, the results can be incomplete combustion. We believe that in many cases it is only retained active exhaust gases that allow effective combustion at maximum engine speeds and any interference or unanticipated effects can cause serious problems. An interesting possibility is to use a deliberately under-sized turbo-charger to inhibit exhaust scavenging but to compensate for reduced breathing efficiencies.

At high engine speeds it may mean that reliance on crank angle for mapping purposes introduces variability in injection volumes, timing and importantly pre-combustion chemistry, which in turn adversely affects emission planning.

These characteristics are inherent in any fuel system that is controlled in an "on-off" manner and tend to make the case for a modulated injector unanswerable if tight emission levels are to be met at high engine speed....a solution that we are working on.

The severity of the induced events is most pronounced in a diesel injector, largely as a result of the high rail pressures. These pressures are necessary to create ultra-sonic flow rates through the nozzle orifices. However, although the effects are significant, the overall result in terms of emissions and in particular of particulates, is not as critical as it can be in a gasoline direct injection engine.

In the diesel engine, the breakdown of the long chain fuel molecules is promoted by the action of hydroxyl radicals that in turn are released as a result of the sono-chemical changes that high...in excess of 1500 meters per second...droplet velocities bring about.

The gasoline direct injection engine operates at higher engine speeds and is far more reliant on marginal sono-chemical changes in order to bring about the necessary pre-combustion chemistry. If the pre-combustion chemical changes (largely the break down of complex fuel molecules into shorter chains that can readily oxidise and can do so at lower temperatures) are not completed, then the engine will suffer from intermittent incomplete combustion, especially at high engine speeds and under load. In these conditions, where the load alters the piston acceleration curves, the limited line pressures possible with gasoline mean that the injector is operating at the edges of its envelope.

In essence, modern engines, both diesel and gasoline, rely on the acoustic cracking of fuel molecules induced by injector design and high rail pressures to meet emission requirements. In particular, the sono-chemistry releases short chain fuel constituents, reducing  $\text{NO}_x$  formation.

It points not only to the importance of highly accurate, responsive rate measurement, but also the importance of matching injector mounting and pump and rail mounting on the test set-up to the actual engine installation. The degree to which the various vibration characteristics influence hydraulic delivery is becoming clearer and these characteristics start with the behaviour of the injector itself but are also affected by vibration within and caused by the common rail, the pump arrangement, the mounting of the injector itself and the absorption of the cylinder head.

It is to provide useful information from which the engine design team can make informed decisions that we are launching a new family of test benches. These are capable of running actual fuels. The changes in fuel components as a result of the injector performance is a vital component in meeting performance and emission targets. The new benches are designed to not only allow testing using actual fuels in a safe environment but are also capable of simulating under-bonnet conditions, both as to temperatures and to a degree simulating the likely operating arrangements of the engine. A standardised surrogate

cylinder head is capable of holding up to eight injectors, together with common rail and supply pump, driven through a quill shaft. The injectors can be mounted in a way that mirrors that likely on the engine.

In this way, a better understanding of the hydraulic delivery of the injector especially at high engine speeds can be achieved, throughout a dynamic range.

We do not however believe that this information is either complete or in itself adequate, however accurate it may be.

We are working to include fuel spectroscopy modules in the bench so that the degree to which ultrasonic flow rates complete necessary pre-combustion chemistry can be measured.

The rate constant for the desired chemistry is perilously close to the time intervals available in high speed gasoline engines. The consequences of incomplete chemistry involve increased  $\text{NO}_x$  levels, potential incomplete combustion and reduced efficiency with raised carbon emissions.

One potential improvement, as we have mentioned earlier, is to inhibit scavenging and as a result increase in-chamber exhaust gas retention. The benefit is that exhaust gas by its nature has a highly active free radical population and in effect throttled exhausts may be necessary for HCCI engines.

However, all of this development depends on accurate and timely data of the characteristics of the proposed fuel systems and we believe that this is now the most important single aspect of engine design. To support these efforts we are launching the new test bench. We are installing engine test facilities to enable correlation of hydraulic delivery with emission and performance outputs. We are shortly to introduce a service where, within our facilities, fuel systems can be characterised and correlated.

Without a clear understanding of the part that free radicals play in combustion chemistry and in down-stream gas changes the most accurate systems, such as AKRIBIS, are limited in their use. INOV8 has the unique ability to combine extremes of measurement accuracy and sensitivity with world class free radical chemistry. Combined with years of experience of engine design and of fuel design, it is I believe a most formidable capability.

References:

- Schmidt, D & Corradini, M. L. The Internal Flow of diesel Fuel injector Nozzles: a review.
- Suslick, Didenko, Fang, Hyeon et al: Acoustic Cavitation and its chemical consequences, Royal Soc.1999
- Reitz, Rolf Deneys. Atomization and Other Breakup Regimes of a Liquid Jet. Ph.D. thesis. Princetown Univ., 1978
- Ruiz, Francisco. "Turbulence Inside a Cavitating Injector Orifice: a Different Animal." ILASS-Americas.pp. 133-137. 1998.
- Reitz, R.D. and F.V. Bracco. "Mechanism of Atomization of a Liquid Jet." *Phys Fluids*. V.26.n.10.1982.
- Soteriou, Celia. Richard Andrews. and Mark Smith. "Direct Injection Diesel Sprays and the Effect of Cavitation and Hydraulic Flip on Atomization." SAE Paper 950080. 1995
- Arcoumanis, C., M. Badami, H. Flora. and M. Gavaises. "Cavitation in Real-Size Multi-Hole Diesel Injector Nozzles." SAE Paper 2000-01-1249.
- Arcoumanis, C., H. Flora, M. Gavaises, N Kampanis, and R. Horrocks. "Investigation of Cavitation in a Vertical Multi-hole Diesel Injector." SAE Paper 1999-01-0524, 1999.
- Schmidt, David P. et al.. "Detection of Cavitation in Fuel Injector Nozzles." 8<sup>th</sup> ISTP Conference. San Francisco. 1995
- Rayleigh, Lord. "On the Pressure Developed in a Liquid During the collapse of a Spherical Cavity." *Phi. Mag.* Vol 34. p.94-98.1917.
- Plesset.M.S., "The Dynamics of Cavitation Bubbles." *Trans. ASME. J. Appl. Mech.* v.16. p. 228-231. 1949.
- Arcoumanis, C., M. Gavaises. and B. French. "Effect of Fuel Injection Processes on the Structure of Diesel Sprays." SAE Paper 970799. 1997.
- Didenko, Y.T. & Pugach, S.P. 1994 *Ultrasonics Sonochem.*
- Didenko, Y.T., Nastich, D.N., Pugach, S.P., Polovinka, Y.A. & Kvochka, V.I. 1994 *Ultrasonics*.
- Flynn, H.G. 1964 *Physics of Acoustic Cavitation in Liquids*.
- Leighton, T.G. 1994 *The Acoustic Bubble*.
- Mason, T.J. & Lorimer, J.P. 1988 *Sonochemistry : theory, applications and uses of ultrasound in chemistry*. Chichester, UK.: Ellis Horwood.
- Mason, T.J. & Luche, J.L. 1996 *Ultrasound as a new tool for synthetic chemists*.
- Suslick, K.S. (ed.) 1988 *Ultrasound: its chemical, physical, and biological effects*. New York: VCH
- Suslick, K.S. & Crum, L.A. 1997 *Sonochemistry and Sonoluminescence*. In *Encyclopedia of acoustics* (ed. M.J. Crocker), vol.1. ch. 26. pp. 27-282. New York: Wiley-Interscience.

Figure 1

2 event injection  
Mean of 5 shots with shot-to-shot variability

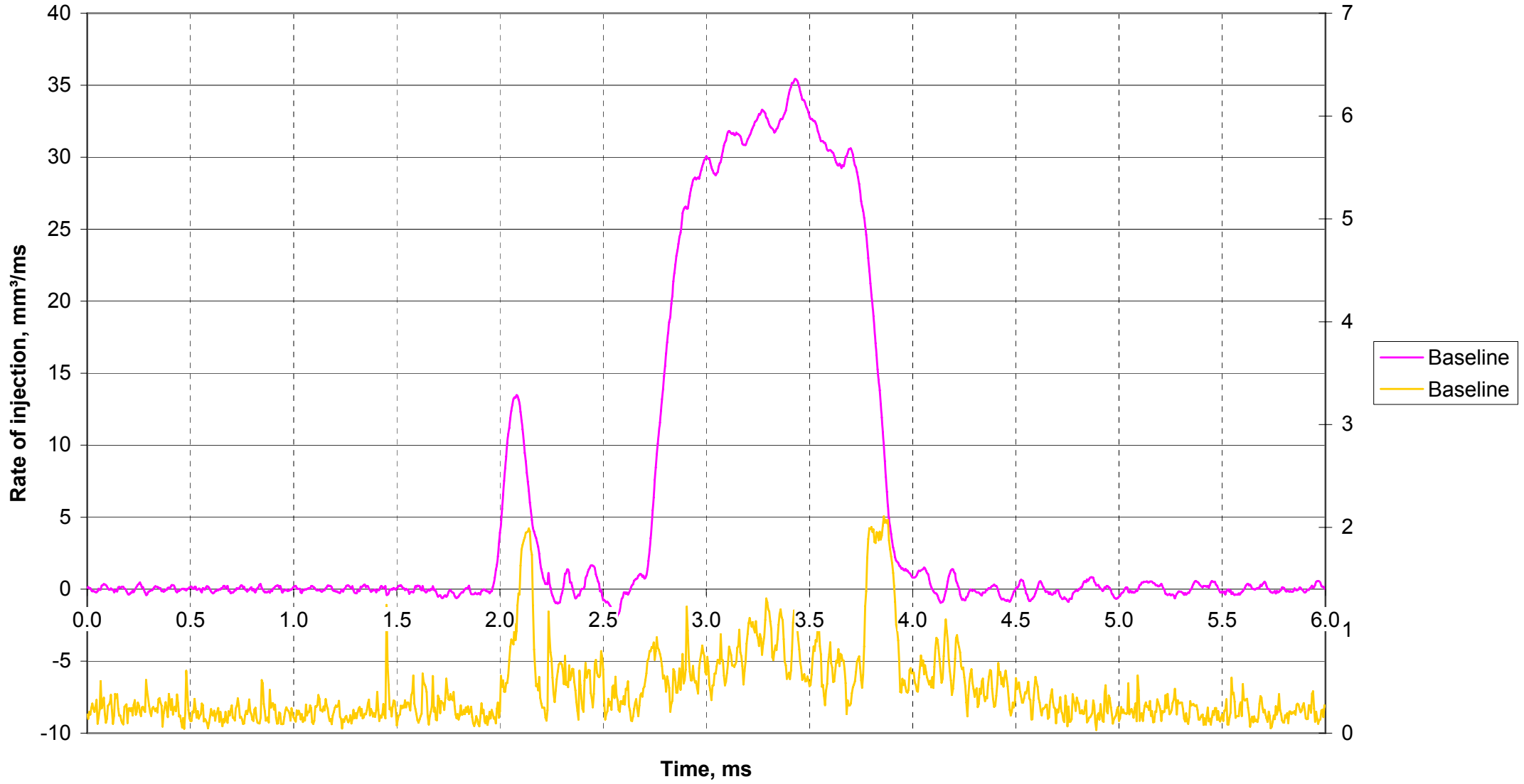


Figure 2

Two close injection events with successfully measured delivery

Tram lines indicate  
50  $\mu$ s separation

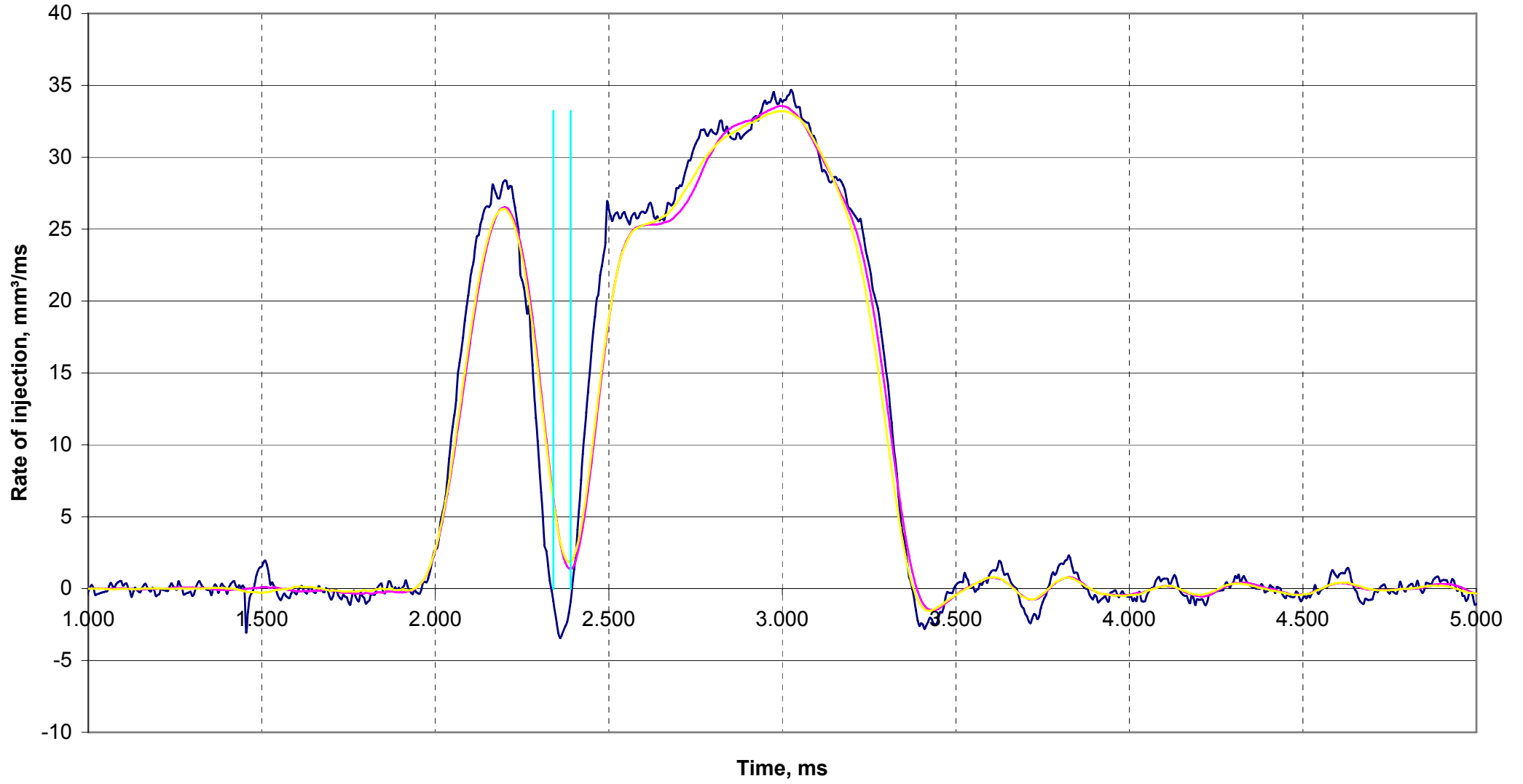


Figure 3

2 event injection at different pressures

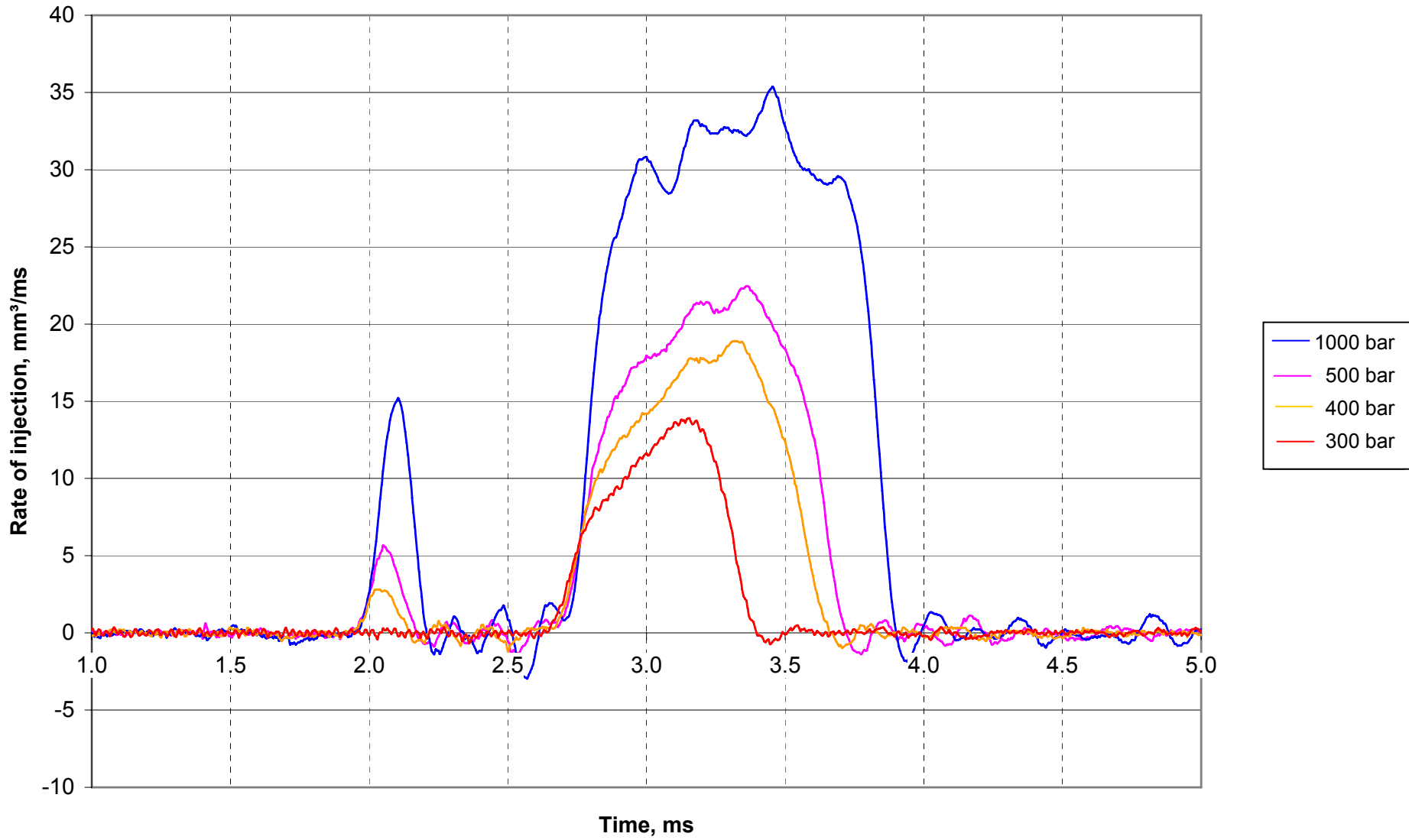


Figure 4

Effect of decreasing event separation on rate disturbance  
1000 bar, T1 420  $\mu$ s, T2 763  $\mu$ s, 20 bar back pressure, one shot data

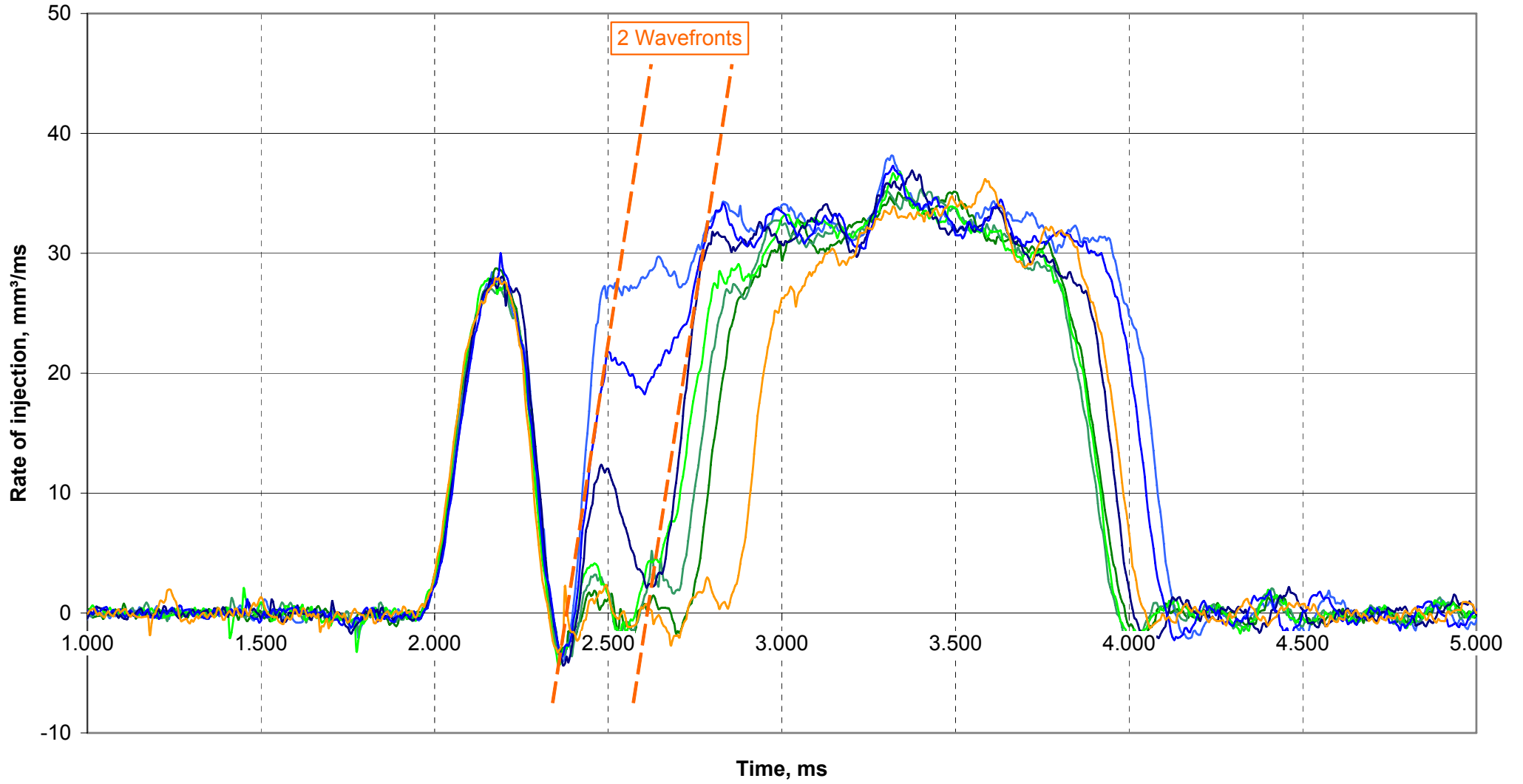


Figure 5

Event timing shift associated with filter symmetry

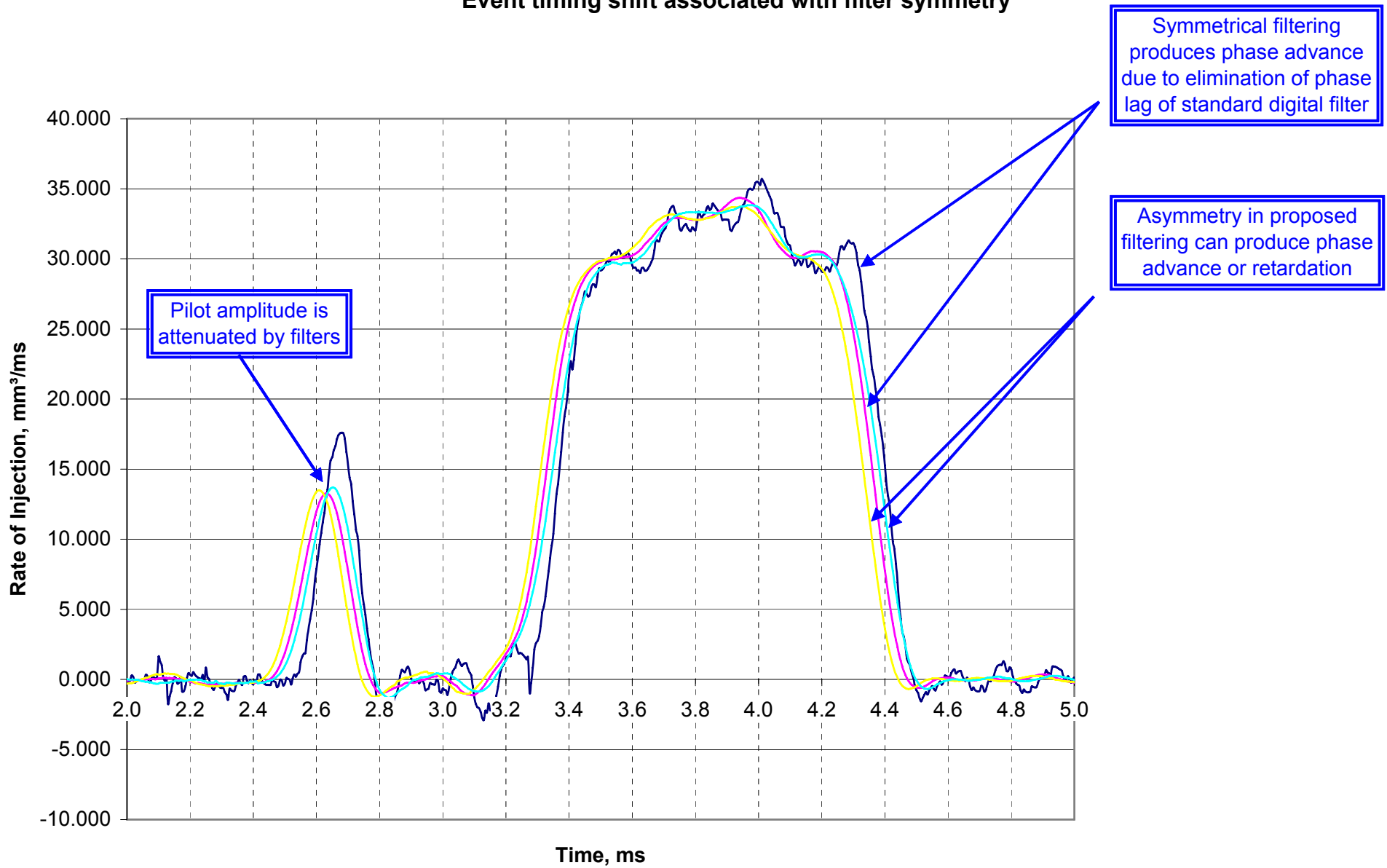


Figure 6

Data from DI data-logger  
Tap-test showing sensitivity of rate signal to vibration

Top of fixture block

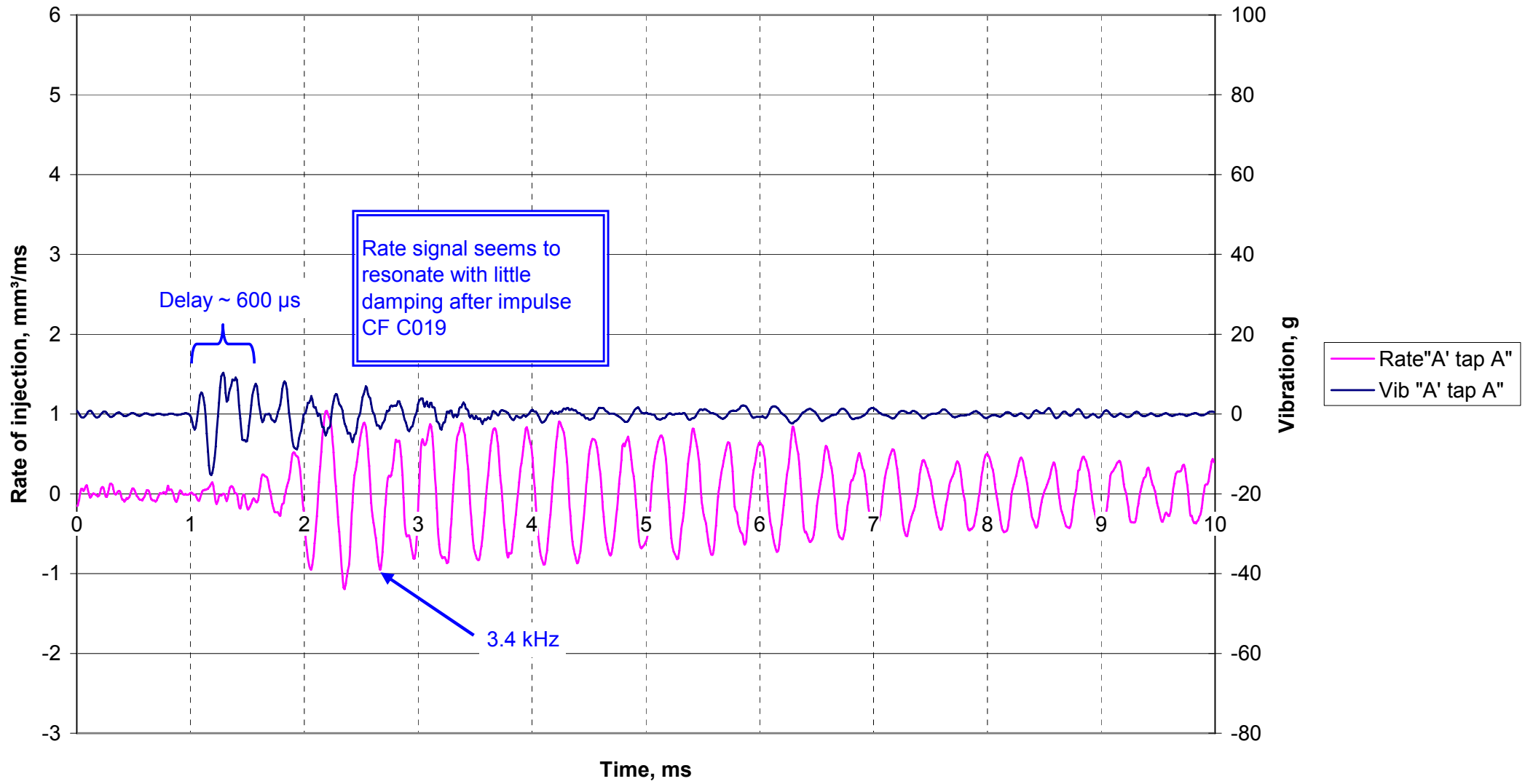


Figure 7

Test point showing rate of injection, injector current and needle lift

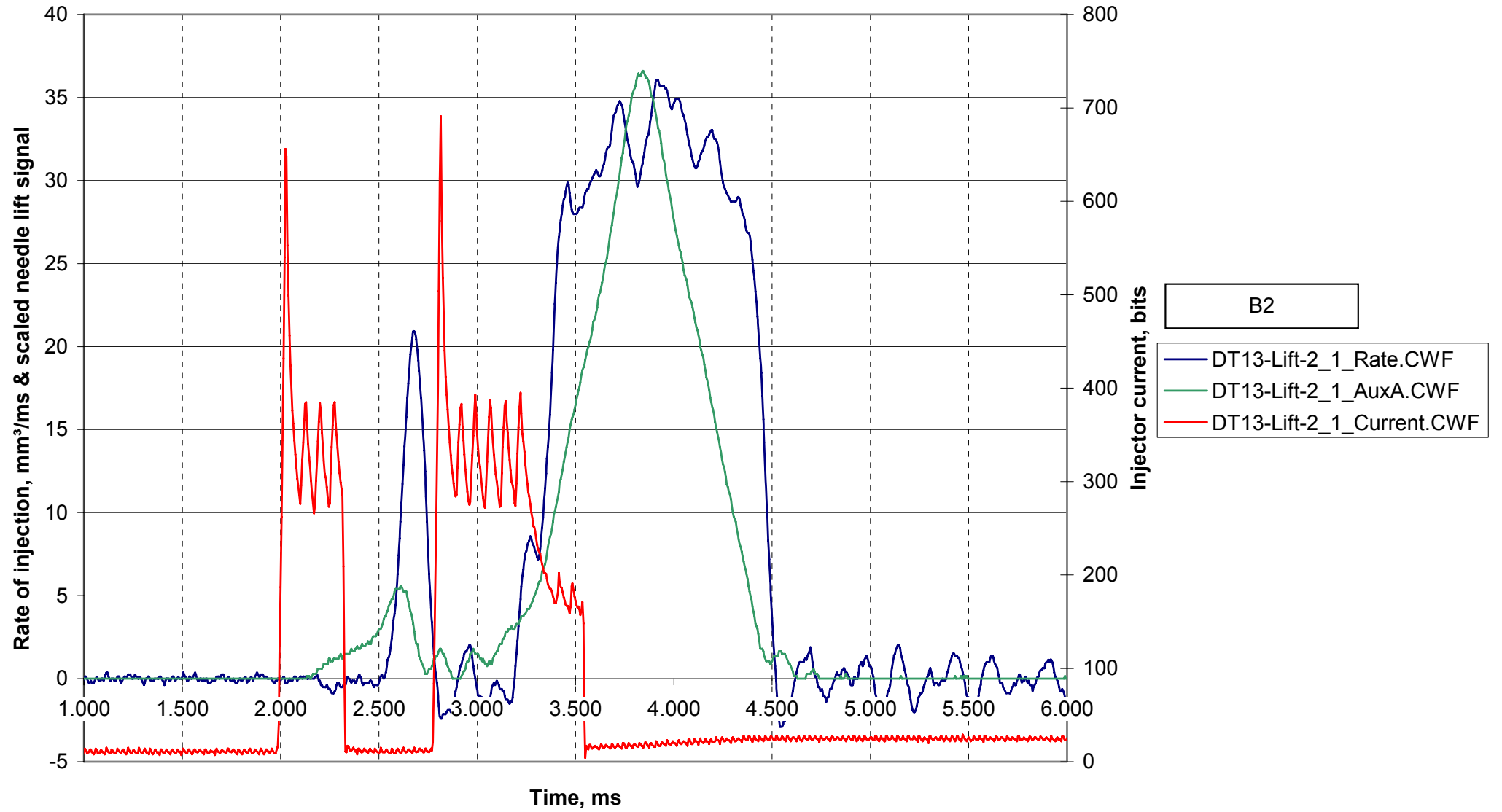


Figure 8

Frequency analyser logged data for an injection event

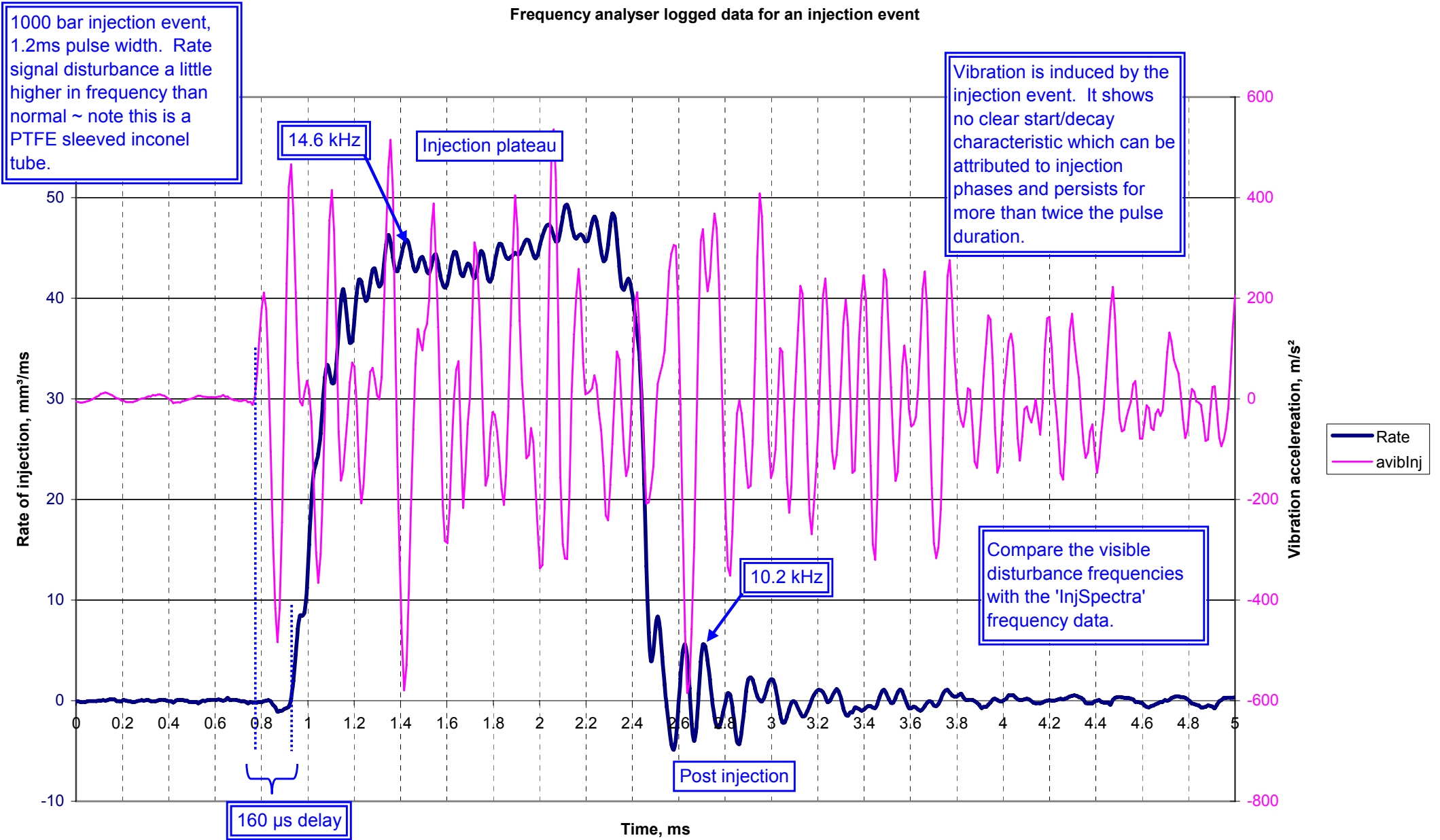


Figure 9

Power spectra from an injection event  
Comparison between rate signal and vibration acceleration on two axes

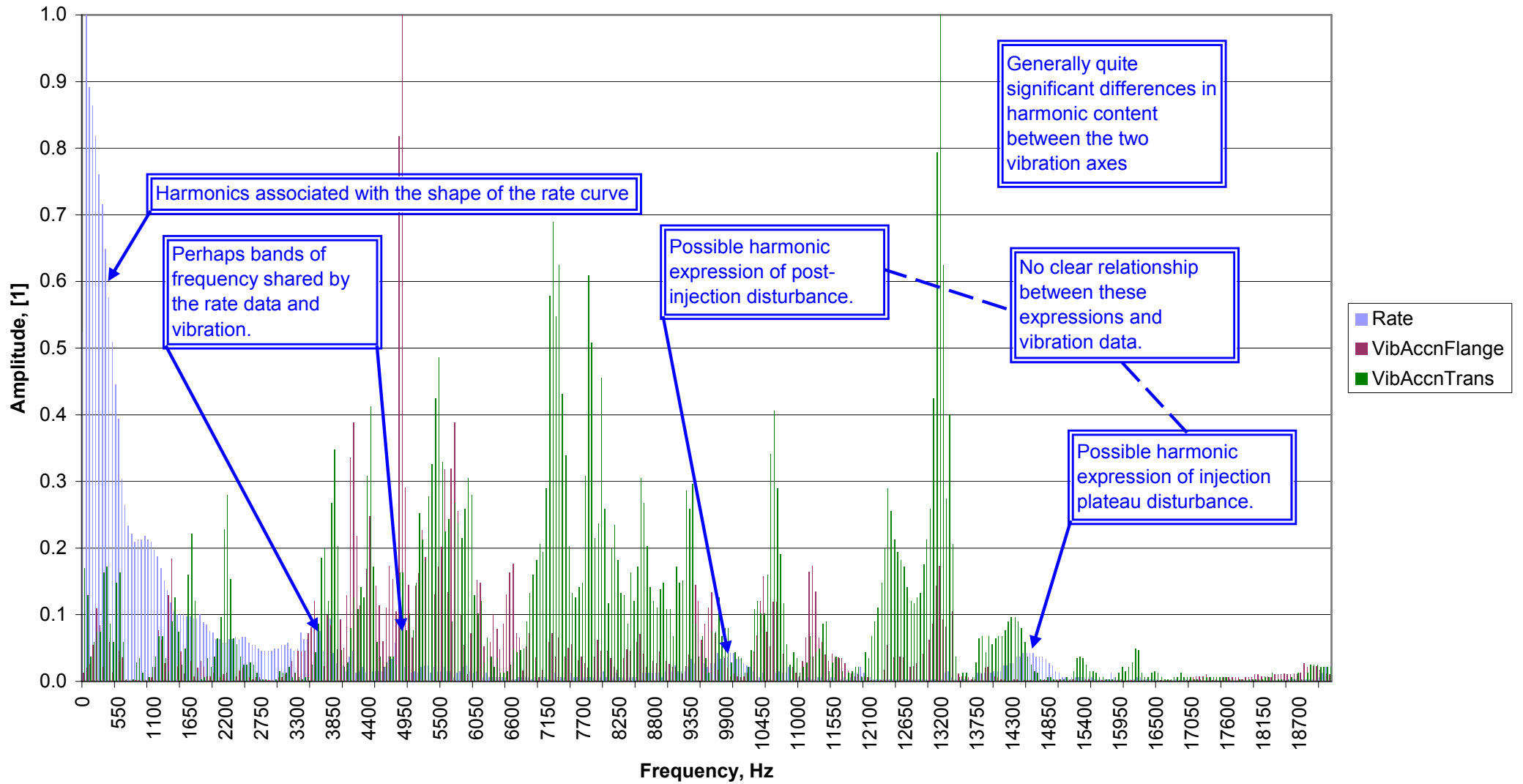


Figure 10

Frequency analyser logged data for hammer tap stimulus  
Hammer tap inducing a vibration response in the Akribis fixture compared with the degree of vibration induced by an injection event  
The vibration is measured axially on the fixture flange

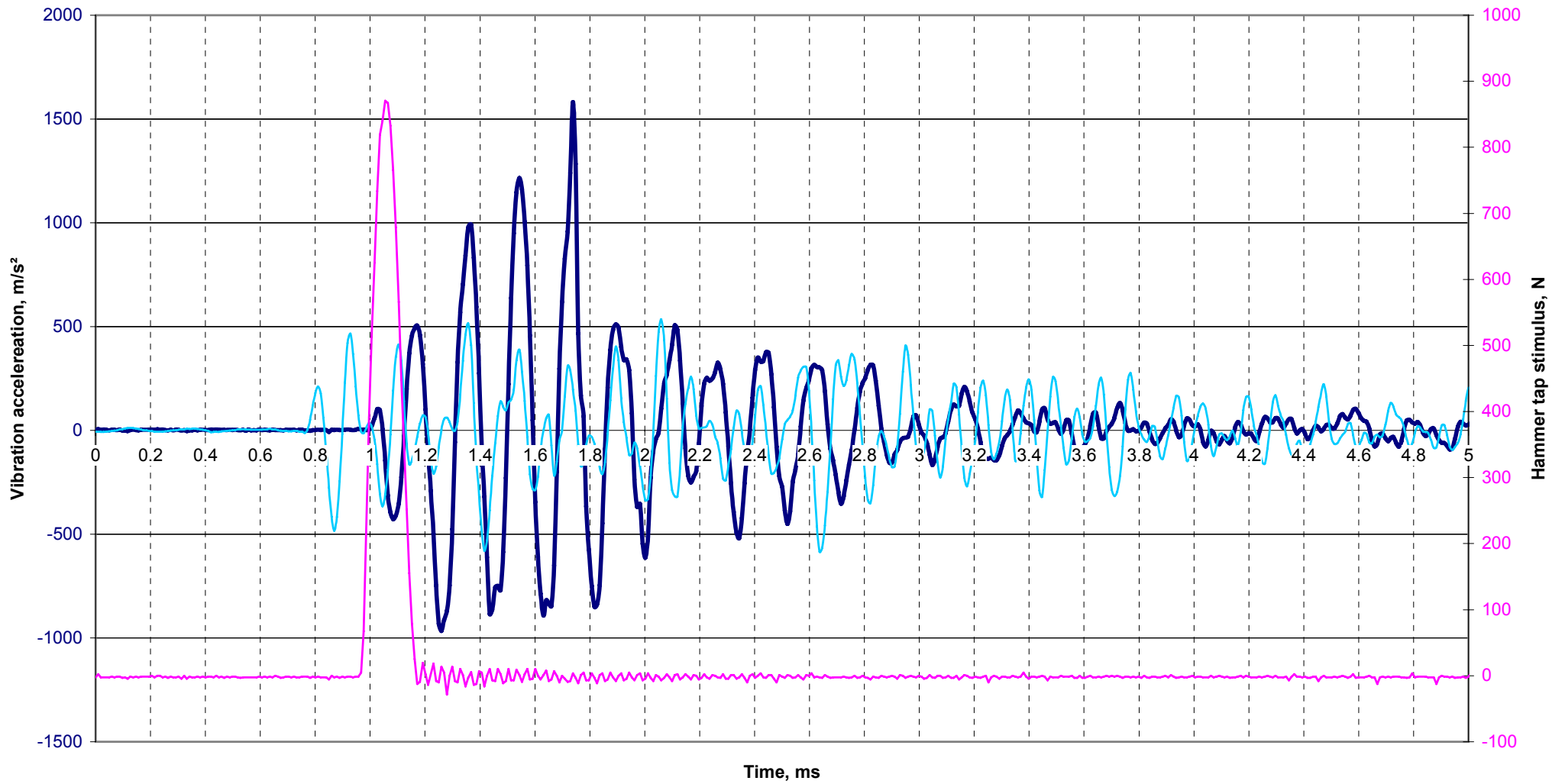
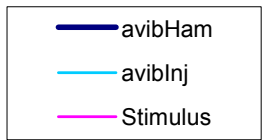


Figure 11

Frequency analyser logged data for an injection event  
Rate signal compared with the rate disturbance caused by a hammer tap stimulus

