

Establishment of Valve Displacement Measurement by Laser Equipment

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ABSTRACT

In order to precisely analyze valve behavior of an automobile engine valve train, we applied a laser displacement meter. We were able to demonstrate that laser measurements are more precise and that lasers produce less noise than a conventional electro optical displacement transducer. However, when the laser method is applied, such problems as irregular reflection of noise on walls around the measured object, and digital conversion noise that is inherent to laser measurements, were encountered. We resolved these problems and improved the laser measurement by changing the shape of the measured surface and the surrounding walls to decrease the noise, and through zero point shift of the input voltage.

As a result of reducing the noise, it became possible to precisely analyze valve behavior, and we isolated the rocker arm re-collision with the valve due to the delay caused by the rocker arm inertia. Additionally, because the laser is more compact than the conventional optical instrument, it is possible to simultaneously measure multiple cylinders.

1. Introduction

Stabilizing valve train behavior is essential for improving engine performance, especially as the required maximum engine speeds are increasing. Valve trains have also become higher performance, as typified by the DOHC coaxial roller bearing VTEC rocker arm shown in Fig. 1.⁽¹⁾

Accordingly, various valve train behaviors are exhibited at high engine speeds, and technical issues must be overcome through detailed analyses.

To achieve this, development periods must be shortened using measurement technology, which provides the highest

accuracy possible, and performance prediction.

Particularly, in terms of valve lift, destruction of the valve train may occur if the bounce phenomenon during valve closing shown in Fig. 2 is 100 to 300 μm or more. Thus it is this phenomenon that determines the maximum engine speed. When analyzing bounce of a few hundred μm , the required measurement accuracy is 3% assuming a full scale of a few hundred μm . That is to say, the noise level must be 10 μm or less. However, achieving a high accuracy measurement of 10 μm within a valve lift displacement of 10 mm or more is extremely difficult, and thus far there are no reported cases of success^{(2)~(6)}

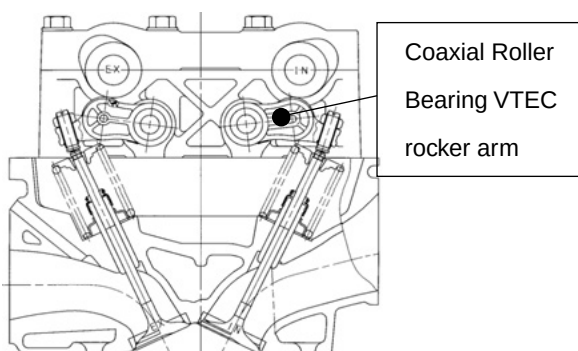


Fig.1 Cylinder head and valve train

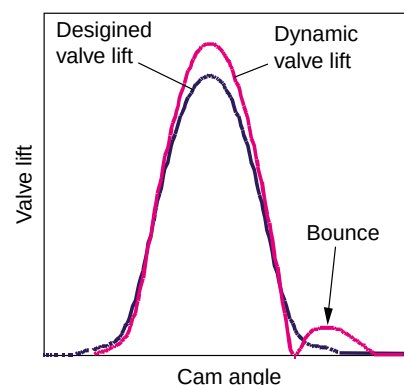


Fig.2 Valve bounce phenomenon at high speed

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The authors, like other researchers, performed measurements using a conventional electro optical displacement transducer, but there was too much noise which made it difficult to analyze phenomena and verify simulations for predicting behavior.

Therefore, the authors focused on laser triangulation method displacement meters as a means of overcoming the issues of electro optical displacement transducers. However, this creates new issues of irregular reflection noise and digital conversion noise, so various measures were taken to resolve these new issues. As a result, the advantages of laser displacement meters allowed accurate measurement of valve displacement, and also fully satisfied the conditions for analysis of phenomena and verification through simulations. The details are reported below.

2. Overview

Semiconductor laser triangulation method displacement meters (hereafter “laser method”) offer the following advantages over electro optical displacement transducers (hereafter “optical method”).

- (1) The required noise level for analyzing bounce is 10 μm or less. The measured noise level of the optical method is 50 μm , and the laser method level is 10 μm or less, which thus satisfies the required accuracy.
- (2) The required sensor head width for simultaneous measurement of multiple cylinders, which is used to analyze and verify the effects of the simultaneous behavior of multiple cylinders, is 30 mm or less. However, although simultaneous measurement of multiple valves is not possible with the optical method due to the camera size, it is possible with the laser method, thus satisfying the requirements.
- (3) The camera set up time is also 30 to 40 minutes per test for the optical method, so the number of test times is also limited. In contrast, the laser method requires only mounting, so set up can be completed in 5 minutes.

However, applying the laser method to the measurement of engine valve train behavior creates the following two issues that had to be overcome before the system could be applied for precise measurement.

2.1. Irregular Reflection Noise due to the Triangulation Method

Measurement is performed from below the valve, that is, from inside the cylinder, so reflection noise is generated by the laser light scattering in the closed area.

- (1) Reflection noise due to the wall shape between the sensor head and the measured object
- (2) Reflection noise due to concave shape of the measured object
- (3) Reflection noise from other walls

2.2. Reducing Zero Cross Noise through Displacement Meter Digital Processing

Zero cross noise is the noise produced by digital-analog conversion when the $\pm$ sign, the maximum digit, changes.

These issues were solved by the methods described

hereafter, enabling accurate analysis of valve behavior. Fig. 3 shows the device fabricated to directly compare the two methods.

Fig. 4 shows a comparison of valve lift measurements for the two methods. Compared to the waveform measured with the optical method, the bounce measured with the laser method clearly has lower noise.

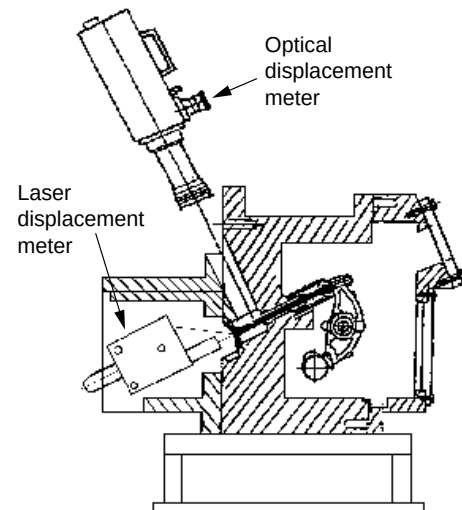


Fig.3 Comparison of optical and laser meter

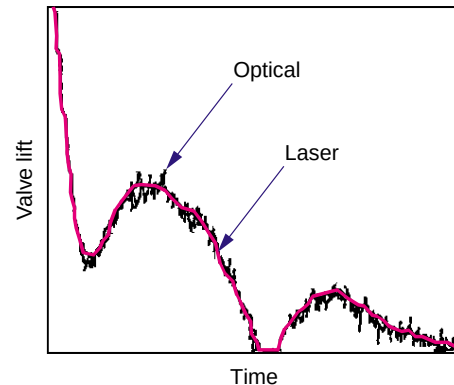


Fig.4 Simultaneous measurement results of optical and laser meter

3. Solution for Displacement Meter Issues

3.1. Reduction of Irregular Reflection Noise

3.1.1. Basic Principle of Laser Triangulation Method

Fig. 5 shows the laser measurement principle.

First, the light from the semiconductor laser strikes the measured object. Part of this scattered light is collected by an imaging lens and it is then formed into an image at the focal position. When the measured object moves in the axial direction of the laser light, the image-forming position changes, and this change in position is sensed by an optical detector.

Therefore, when the sensor head is installed in a closed

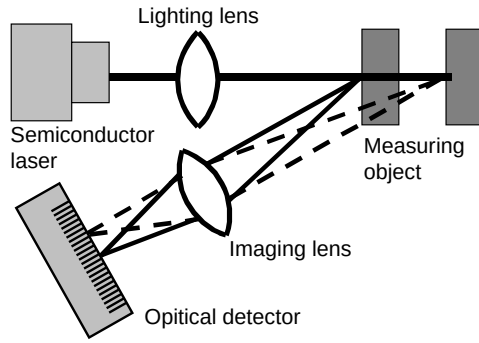


Fig.5 Locational detection of triangular method

area such as inside the combustion chamber, the secondary reflected light produced by the surrounding walls enters the imaging lens in addition to the reflected light from the measured object. This secondary reflected light also strikes the optical detector, creating irregular reflection noise.

Fig. 6 shows data measured by a laser displacement meter without countermeasures. If a narrow channel exists between the measured object and the laser sensor head, noise equivalent to displacement of $400\text{ }\mu\text{m}$ is produced.

Therefore, the measures described in the following section were taken to reduce irregular reflection noise.

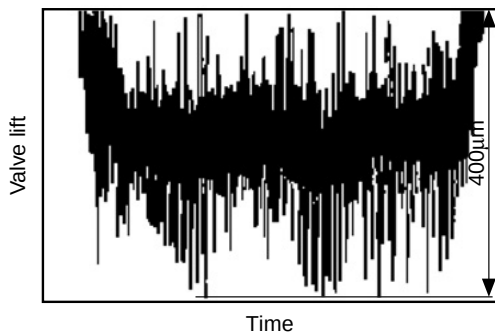


Fig.6 Measured data by laser method (Initial data)

3.1.2. Reduction of Irregular Reflection from around the Measured Object

Scattered light from the valve being measured reflects off the narrow channel walls, passes through the imaging lens, and enters the optical detector. As a result, light is irradiated to a different optical detector position than the light from the measured object, creating noise. Therefore, countermeasures were taken by changing the surrounding wall shape from that shown in Fig. 7 to the concave shape shown in Fig. 8.

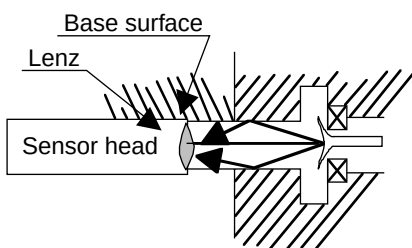


Fig.7 Wall reflection in narrow channel

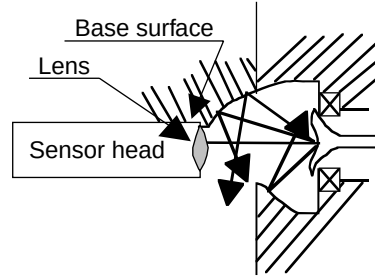


Fig.8 Wall reflection in wide channel

As a result, the noise was reduced by approximately half, to $230\text{ }\mu\text{m}$ as shown in Fig. 9, but this still does not meet the target accuracy of $10\text{ }\mu\text{m}$ or less. Furthermore, it is approximately five times greater than the noise level obtained through simultaneous measurement using the optical method (Fig. 10), and thus is not at a practical level.

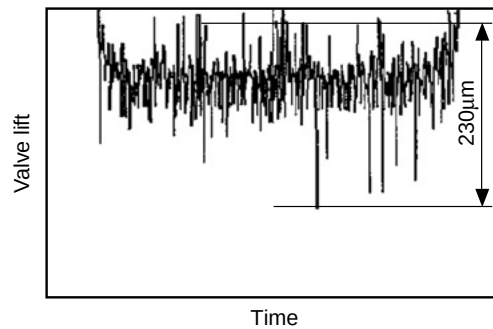


Fig.9 Data measured by laser method (modified wall shape)

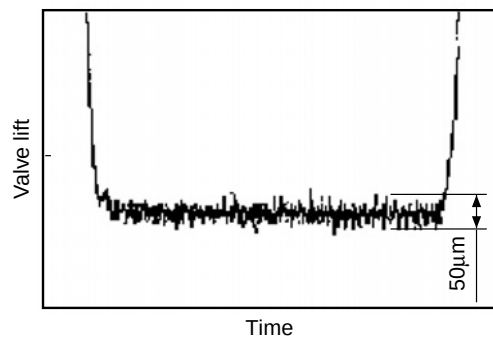


Fig.10 Data measured by optical displacement meter

3.1.3. Eliminating the Concave Shape of the Measured Object

When the measured surface has a concave area, a round spot reflection of the laser is observed. This is thought to increase noise produced by reflection, even in the circular portion around the bottom surface. Therefore, the concave shape was eliminated as shown in Fig. 11. This reduced the noise to $25\text{ }\mu\text{m}$ as shown in Fig. 12.

However, even when the countermeasures through section 3.1.3 were implemented, the noise was still not

reduced to 10 μm or less. The cause for this is thought to be the entry of irregularly reflected light from other surrounding walls. Therefore, countermeasures were taken, as shown in Fig. 13, whereby a conical tube with a rough, non-reflective inner surface was used to prevent the entry of external irregularly reflected light from outside of the cone.

As a result, the noise level was reduced to 15 μm as shown in Fig. 14. However, noise spikes sometimes still occurred. This issue was resolved by the method described in the following section, 3.2.

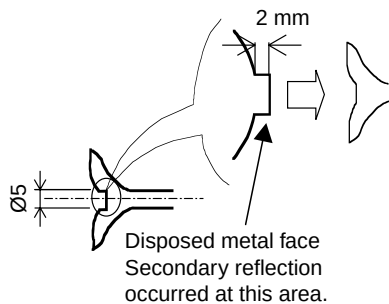


Fig.11 Abolishment of concave shape

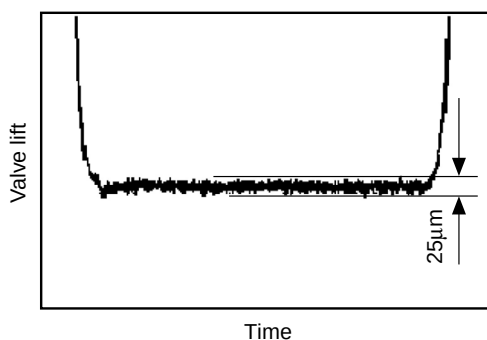


Fig.12 Data measured by optical method

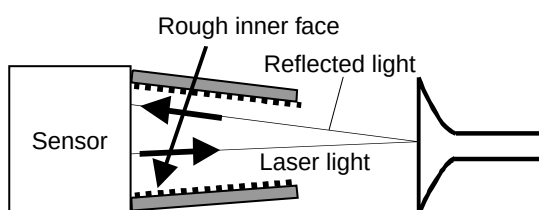


Fig.13 Non-reflective pipe

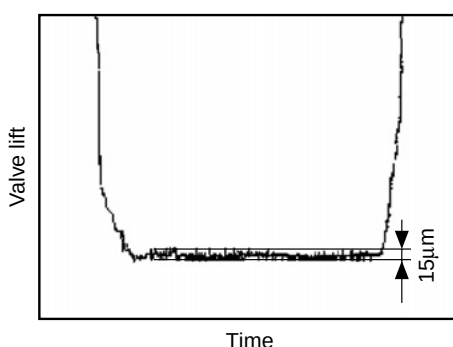


Fig.14 Data measured by laser method (Non-reflective pipe)

3.2. Reduction of Zero Cross Noise

When performing triangulation method using digital circuits, the analog output from the detector amplifier is converted from analog to digital, translated by a calibration map, and then converted from digital to analog again and output as shown in Fig. 15 below. Therefore, the noise produced by the detector amplifier is not amplified, and the analog output noise is minimized.

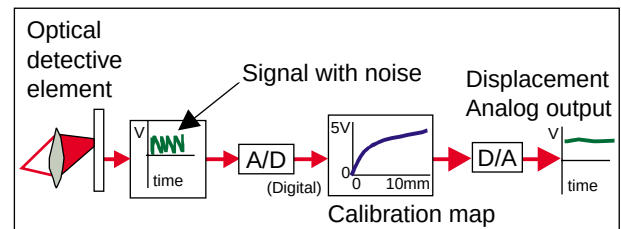


Fig.15 Block diagram of semiconductor laser amplifier

However, digital measurement is subject to the phenomenon known as zero cross noise. When displacement changes from a positive to a negative or vice versa, the sign changes accordingly. In digital representation, the sign ($\pm$) digit is the maximum digit, and switching this digit causes all bits to change from 0 to 1 as shown in Fig. 16. This is converted from digital to analog, so a large instantaneous voltage change occurs, producing noise spikes called “gritty noise.” Therefore, when continuously measuring displacement around zero, noise spikes constantly appear on the waveform. As a countermeasure, when measurement accuracy is needed near zero, noise is reduced by shifting the zero point and then reshifting this same amount during a calibration processing as shown in Fig. 17.

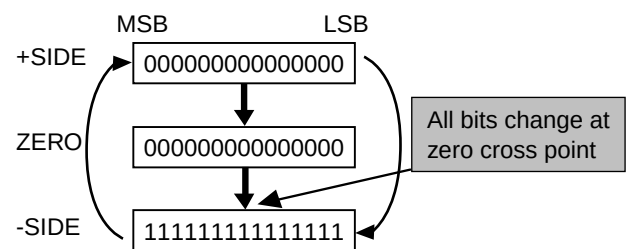


Fig.16 Figure of “Zero cross noise”

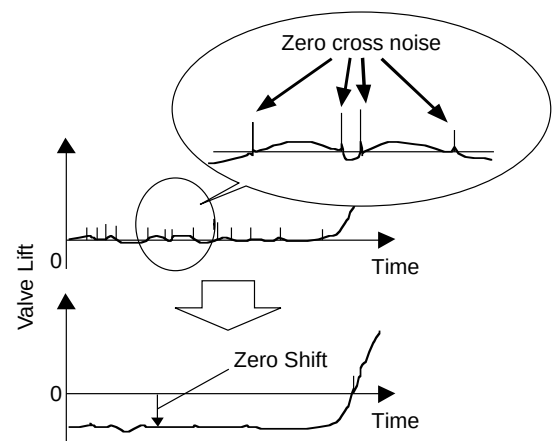


Fig.17 Improved pulse shape of “Zero cross noise”

Implementing the above four countermeasures reduced the noise to 10 μm or less as shown in Fig. 18.

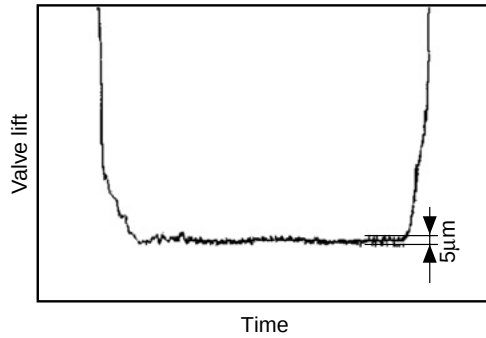


Fig.18 After reduced zero cross noise (final)

3.3. Summary of Noise Reduction Effects

As shown in Fig. 19, the above improvements enabled a reduction in noise, compared to the optical method, sufficient for detecting valve bounce.

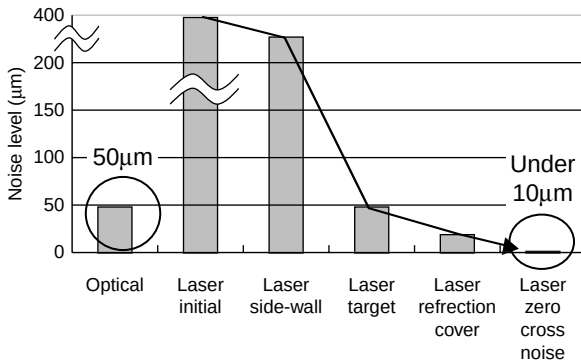


Fig.19 Transition of noise reduction

4. Effects of this Measuring Method

4.1. Improved Analysis Capabilities at High Engine Speeds

Fig. 20 shows the results of bounce during valve closing as measured by the optical method. Here, the details of why a large bounce occurs under these measurement conditions are unclear.

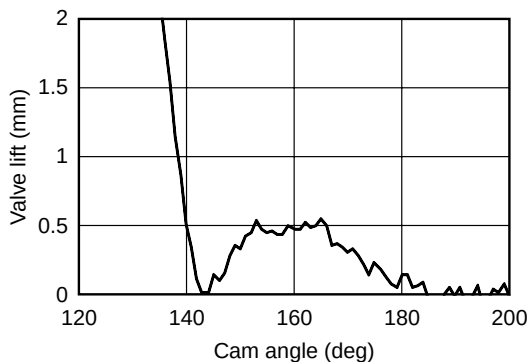


Fig.20 Valve bounce measured by optical method

However, when the laser method developed through this research is used, a small jump can be confirmed as shown in Fig. 21.

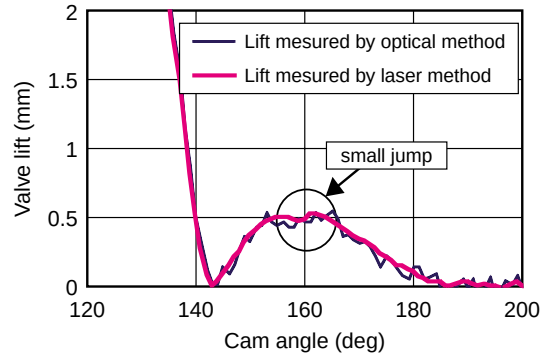


Fig.21 Valve bounce measured by optical & laser method

From this motion, it was thought that collision with some other part occurs at this time. Therefore, simulation calculations were carried out, whereby it was confirmed that similar jumps were reproduced as shown in Fig. 22.

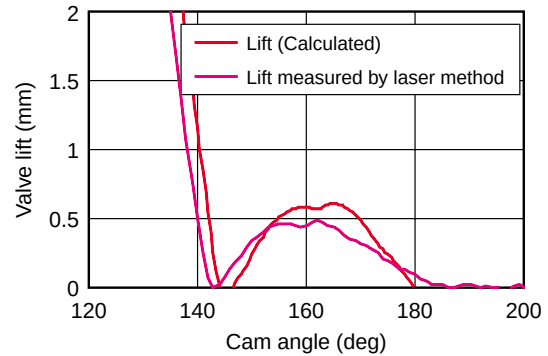


Fig.22 Bounce measured by laser & simulated result

Furthermore, the behavior of adjoining parts was also analyzed using simulation models. These results showed that re-collision with the valve due to the delay of the rocker arm inertia as shown in Fig. 23 caused the valve to bounce.

In this manner, at high engine speeds, the valve makes slight collisions during the period of valve opening to closing. Therefore, when analyzing the detailed causes of behavior,

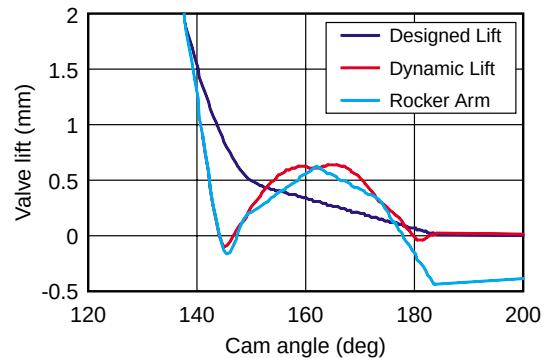


Fig.23 Valve simulation analysis

this laser measurement method is an essential technology for understanding changes in behavior of 10 μm or less.

4.2. Simultaneous Measurement of Multiple Cylinders

Two laser displacement meters can be mounted to each cylinder, so eight valves can be measured simultaneously as shown in Fig. 24. This enables comparison of behavior differences between cylinders, and makes it possible to confirm the effects of cam torsional and flexural rigidity between cylinders. It also enables analysis of the effect of rocker arm shaft flexural rigidity when constructing simulation models for analyzing the behavior of multiple cylinders simultaneously. In addition, fluctuations such as that shown in Fig. 25 can be simultaneously measured, so that this method can also be utilized to analyze the causes of abnormal phenomena resulting from the compounded behavior of multiple cylinders, rendering it a highly effective method.

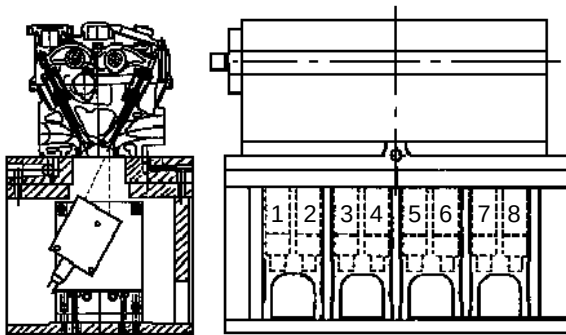


Fig.24 Position of laser sensor heads

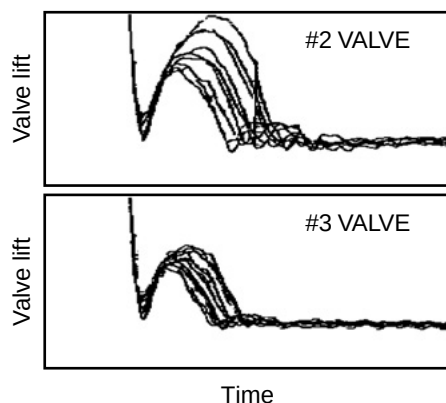


Fig.25 Multi-cylinder simultaneous data

5. Conclusions

The following issues arise when measuring valve train behavior with a laser triangulation method displacement meter.

- (1) Irregular reflection noise produced by walls
- (2) Zero cross noise during analog-digital conversion

Solving these issues made it possible to assure the required measurement accuracy of 10 μm or less.

This allowed detailed valve train collisions occurring at high revolutions to be extracted, and enabled highly efficient analysis of compound issues and other phenomena through simultaneous measurement of multiple cylinders.

Efforts will be made in the future to apply this technology to the measurement of other parts as well.

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