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ABSTRACT

The newly developed optical instrument for vibration analysis is based on the laser Doppler effect that can be used to measure the vibration velocity of object surface points. The new system "SOVAS" (Scanning Optical Vibration Analysis System) analyzes the vibration amplitude of whole surface areas by means of computer controlled laser scanning and fast Fourier transform of the velocity signals derived from Doppler frequency modulation. As results frequency spectra of single points as well as vibration patterns of up to seven simultaneously measured frequency ranges can be displayed. The presented paper gives a detailed description of "SOVAS" and some typical applications in vibration analysis of car body and engine parts.

THE DOPPLER EFFECT in the scattering of laser light at moving objects forms the basis for a number of methods for non-contact measurement of velocity. The main application is the measurement of flow velocities in liquids and gasses, the so-called laser Doppler anemometry (1),(2).* This is the intended application for almost all commercial laser Doppler instruments being developed.

Another application for laser Doppler measuring technology is the time-resolved measurement of the vibrational velocity of the surfaces of solid bodies. Up to the present time, this has been realized in only one commercial instrument, the "Vibrometer" from Dantec (formerly DISA, Denmark). This instrument supplied a time-resolved signal for the vibrational speed of individual surface points.

Within the scope of further development for this measurement procedure, a surface-scanning vibration analysis system was to be established that meets the following requirements:

- Rapid measurement of vibration data (amplitude, velocity, acceleration) of the total surface of objects.
- Frequency analysis of the vibration signals.
- Reconstruction of the vibration distributions.
- Measurement in the acoustic range of frequencies from 10 Hz up to 12 kHz.
- Measurement with external and self excitation (e.g., an engine or a complete vehicle on the testing stand).

The present paper reports on the fundamentals of the laser Doppler vibration measurement technique, the construction of the surface-scanning vibration analysis system, and several interesting applications in automotive engineering.

FUNDAMENTALS

For the measurement of the surface velocity of solid bodies, the reference beam method is used (3), (4). This principle is schematically outlined in Fig. 1. A laser beam (frequency f_L) is focussed on the object. The light scattered back in the direction of incidence undergoes a frequency shift f_D that is proportional to the velocity component of the object in the direction of the beam:

$$f_D(t) = v(t) \cdot 2 \cdot \cos \vartheta/2$$

In order to measure this slight frequency shift, one superimposes on the light reflected back a reference beam with a defined frequency shift of f_0 = 40 MHz (Heterodyne detection). The separation and frequency shift of the reference beam are attained here by means of a Bragg cell whose 0th order of refraction forms the

* Numbers in parentheses designate references at end of paper.

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object beam and whose 1st order of refraction forms the frequency shifted reference beam. The photo detector (PIN or avalanche diode) records the beating signal between the object amplitude A_s and the reference amplitude A_r:

$$I = |A_s + A_r|^2 = |A_s|^2 + |A_r|^2 + A_s A_r^* + A_s^* A_r$$

$$A_s(t) = A_s' \exp[2\pi i (f_L + f_D) t]$$

$$A_r(t) = A_r' \exp[2\pi i (f_L + f_0) t]$$

$$I = |A_s|^2 + |A_r|^2 + 2 A_s' A_r' \cos[2\pi (f_0 - f_D) t]$$

These calculations show that the resulting signal no longer contains the light frequency, but only the measurable beat frequency $f_0 - f_D$.

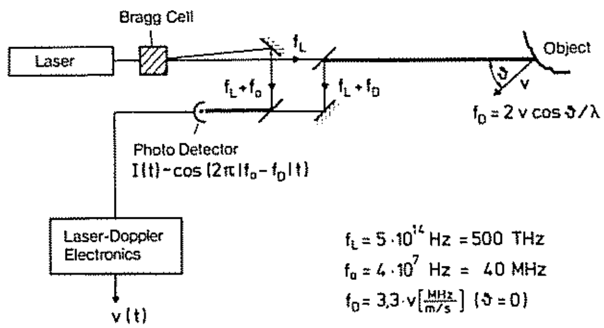

Fig. 1: Principle of laser Doppler vibration measurement

The frequency modulation of the signal must be analyzed and converted into a v(t) signal. The procedure - electronic "downshifting" and signal analysis using a frequency tracker - was suggested by Buchhave (4), has been realized in the Dantec Vibrometer, and has been adopted for the "SOVAS" as well.

The ranges of measurement as shown in Fig. 2 result essentially from the properties of the tracker.

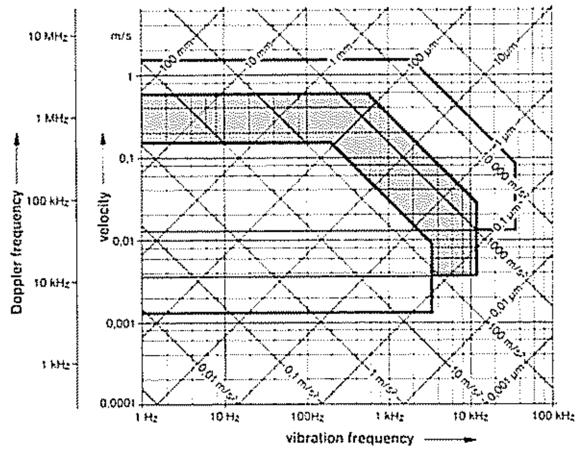

Fig. 2: Measuring ranges for the Vibrometer

The velocity (Doppler frequency), amplitude, and acceleration of acoustic vibrations are recorded over the frequency. The three upper measuring ranges of the tracker are entered in this diagram. The limits result from

(a) the maximum detectable Doppler frequency (horizontal lines at top),
(b) the capability to follow changes in velocity (lines of equal acceleration),
(c) the data rate (frequency of digitalization), and
(d) the 8 bit depth of digitalization of the tracker (horizontal lines at bottom).

Almost all acoustic vibrations that are of interest can be covered with this. Problems can occur only in the range of higher frequencies and small amplitudes. Here, if need be, other methods of electronic laser Doppler signal processing would be more suitable.

OPTICAL HARDWARE

The scanning optical vibration analysis system is based on a new measuring head with a laser deflection unit (Fig. 3). In design, special emphasis was put on a rugged construction that makes it possible to take measurements even in a rough industrial environment. A drawing is shown in Fig. 3.

The light source is a 15 mW-HeNe-laser that has been provided with an etalon for longitudinal monomode operation. The separation of the object and the reference beam takes place, as outlined in Fig. 1, in a Bragg cell. The object beam passes through the polarization beam splitter with attached λ/4-plate, an expansion lens, and is then focussed by the lens via two reflecting mirrors on the object. The backscattered light is collected on the same path and reaches the photo detector, an avalanche diode, together with the reference beam.

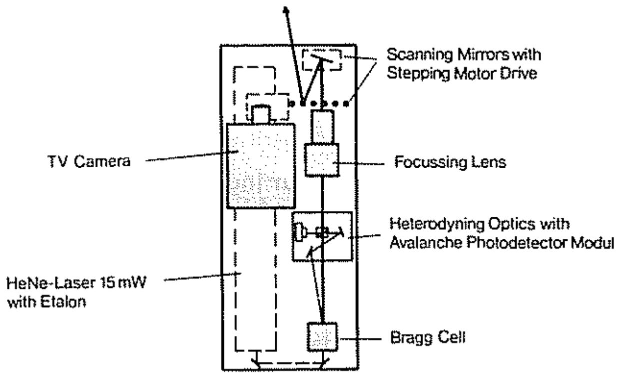

Fig. 3: SOVAS measuring head

The two mirrors for the horizontal and vertical deflection of the object beam are moved by computer controlled step motors. In addition to the laser Doppler optics, a television camera is installed in the measuring head that takes a picture of the object being scanned for the presentation of the results. Fig. 4 shows the total measuring system, including the measuring head, on the engine test stand.

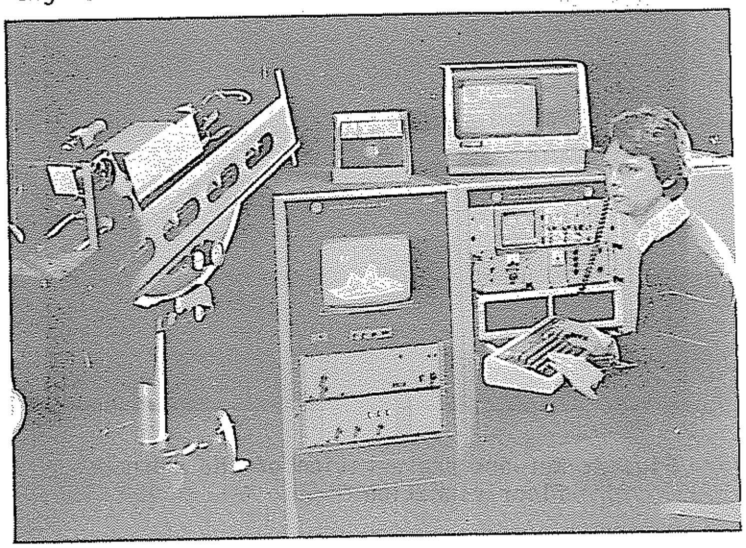

Fig. 4: SOVAS in use on the engine test bed

SOVAS Data Processing

A Digital LSI 11/2 minicomputer with terminal, Floppy-Disk drive, picture memory and RGB monitor is used for data processing. It is supplemented by an Analogic AP 400 array processor, which does the fast Fourier transformation of a signal with 1024 sampling points in 3.4 ms. The system analysis of the vibration signals.

The principle of the data processing from the recording of the signal to the reconstruction of the vibrational distributions has been outlined schematically in Fig. 5.

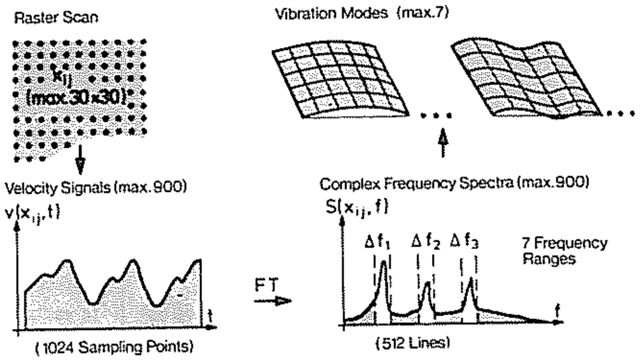

Fig. 5: Data processing

Controlled by the computer, the laser beam scans a preset measurement area point-by-point. The bounds can be defined with cursor lines on the monitor displayed object. The step motor control is tuned in by running up to the corner points of the measurement area. The number of scanning points with the rectangular measuring area can be freely selected up to a maximum number of 30 x 30 points in x and y direction.

At every measuring point, the laser Doppler electronic system analyzes the signal of the photo detector and prepares the resultant velocity signal - already digitalized - for the computer. Using the array processor, a complex vibrational spectrum with 512 lines is calculated immediately from that, and, if needed, converted into an amplitude or an acceleration spectrum.

The levels (maximum, integral, or average) for a maximum of seven frequency ranges can be stored from each of these individual spectra, in order later to reconstruct a vibration pattern from the data stored for each frequency range. In addition, it is also possible to represent individual or averaged spectra in order to investigate interesting ranges of frequencies.

Because the data are acquired at the various measuring points not simultaneously but one after the other, it is possible to measure the relative phase in the vibration signals only by taking into consideration an additional reference signal. This signal can be produced by a vibrational pickup at any point desired on the object and triggers the start of data acquisition for each measuring point.

RANGES OF MEASUREMENT - The speed of scanning is limited primarily by the frequency of the vibrations to be studies: if a frequency resolution of Δf = 2 Hz in the spectrum is desired, the time required for measurement for the individual point is 0.5 sec. On the other hand, the time for data processing is scarcely of any importance, since it amounts only a few milliseconds.

Fig. 6 provides an overview of the ranges of measurement that have been realized in the system.

	Software Range 1		Software Range 2		
Tracker Range	3,3 MHz	10 MHz	1 MHz	3,3 MHz	10 kHz
Data Rate	25 kHz	71 kHz	7,5 kHz	25 kHz	71 kHz
Sampling Rate	2 kHz	2 kHz	7,5 kHz	25 kHz	71 kHz
Measuring Time of 1 Point	494 ms	487 ms	137 ms	41 ms	14 ms
Frequency Resolution	2 Hz	2 Hz	7,3 Hz	24 Hz	70 Hz
Max. Frequency	1 kHz	1 kHz	3,7 kHz	12 kHz	36 kHz
Measuring Time (400 points)	4 min	4 min	1 min	20 sec	14 sec

Fig. 6: Measuring ranges for the system

Range 2 is determined by the data transfer rate (measurement interval) of the tracker in its various ranges of measurement. In range 1, importance was put on a frequency resolution of 2 Hz in the vibration spectrum. With 518 lines, the maximum frequency is then approx. 1 kHz. If all ranges are taken together, the entire range of frequencies from 10 Hz up to 12 kHz that is of interest in acoustics is covered.

Depending on the range of measurement, the measuring time that results for the scanning of 400 points is on an order of magnitude of from 20 secs. up to a few minutes.

PRESENTATION OF THE MEASUREMENTS

The print-out of the results of measurement (spectra and vibrational patterns) is made graphically on the colored monitor. An X-Y-plotter can be connected to produce hard copies.

There are two routines available for the illustration of vibrational patterns that have been measured. The "network presentation" supplies a persepctive picture of the amplitude distribution on the horizontal measuring point grid as shown in Fig. 7. The network presentation is suitable above all for qualitative evaluation of the mode structure. In the "set" drawing mode (Fig. 8), the measuring point grid and the level values are graphed over the black and white image of the object as a deflection of the lines of measured points. In this way, it is possible to read off the levels for individual measuring points.

Additional information on the relative vibrational phases is possible in the "set" drawing mode by using colored identification of the level lines. The computer has available 15 colors to identify various phase sectors.

In the network graphics, two ranges of a different phase can be identified by entering the amplitudes positive or negative in each case. This is sufficient for harmonic vibrations, since only phase differences of 180° occur.

APPLICATIONS

Use of the SOVAS measuring system is suggested whenever the distribution of vibrational amplitude in various ranges of frequency across a surface area is to be determined for stationary vibrations. Because this is a non-contact process, it can also be used on thin plates, on hot or inaccessible parts, and on rotating objects.

Even in the testing phase for the instrument, an entire series of vibrating objects from automotive engineering has been studied, including auto body parts with differing acoustic excitation, vehicles with the engine running, cylinder heads, ignition distributors, engine oil pans on the test stand, and moving parts such as toothed belts, rotating drive shafts, and wheels on the vehicle on the chassis dynamometer.

Figs. 7 to 18 show several interesting examples from these measurements.

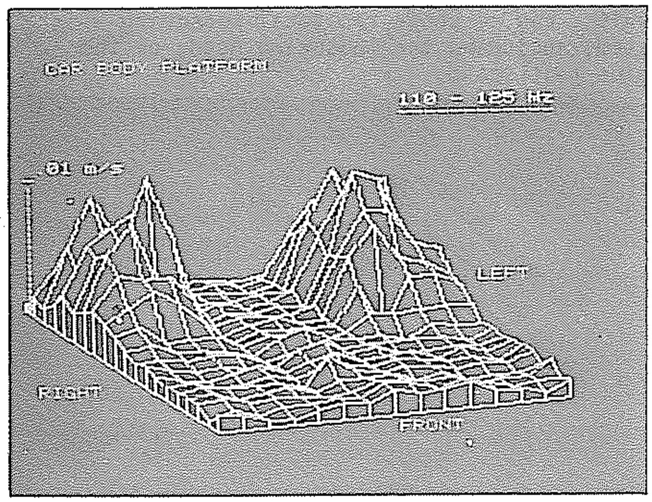

Fig. 7: Network presentation of the vehicle floor vibration

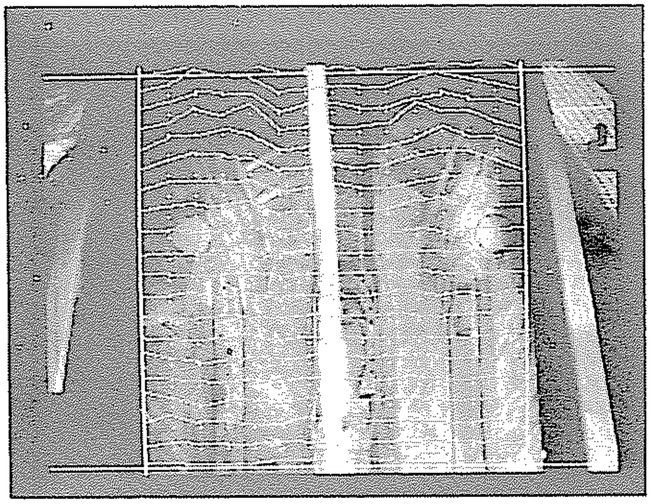

Fig. 8: TV picture of the floor of an auto body, the vibrational behavior of which was studied with excitation with "pink" noise (20 - 250 Hz). Shaded in the picture are the grid of measuring points and the vibrational amplitude in the frequency range as a deflection of the lines in that grid.

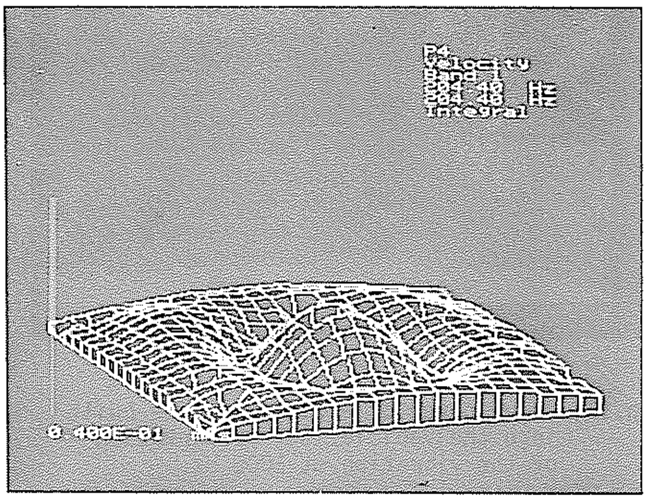

Fig. 9: Vibration of a plate clamped in place on all sides under sinusoidal excitation at 200 Hz

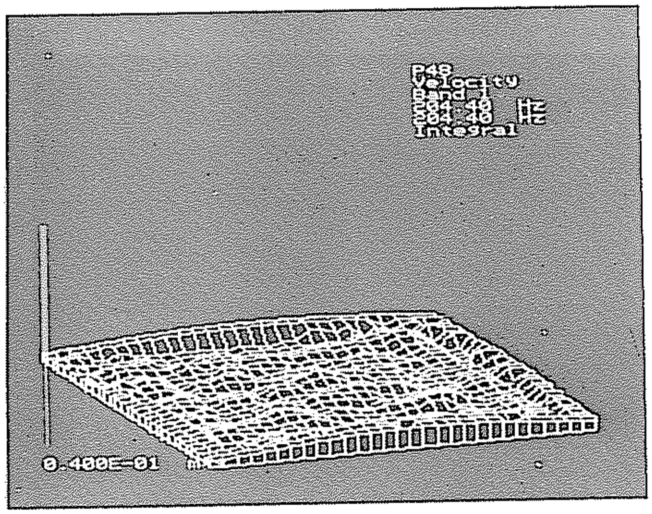

Fig.10: Vibration of the surface of damping foam on the same plate as shown in Fig. 9.Fig. 9 and Fig. 10 were obtained within the scope of an investigation of the behavior of thick coatings of insulation materials on vi brating sheet metal surfaces.

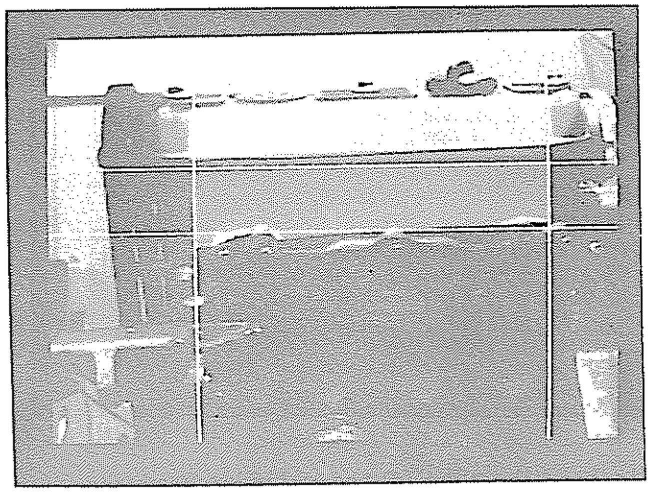

Fig.11: Side view of a cylinder head on an engine body. Being investigated were the vibrations of the side wall that were excited by the valve gear at certain rotational speeds. Fig. 12 to Fig. 15 show the vibration distributions occuring simultaneously.

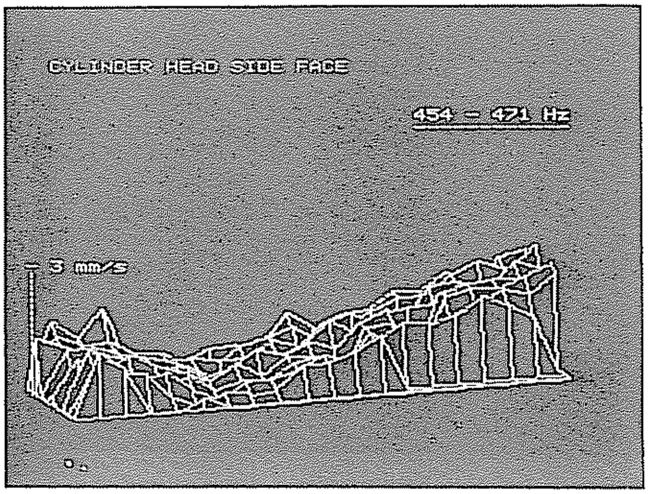

Fig.12: Vibration of the cylinder head at 460 Hz

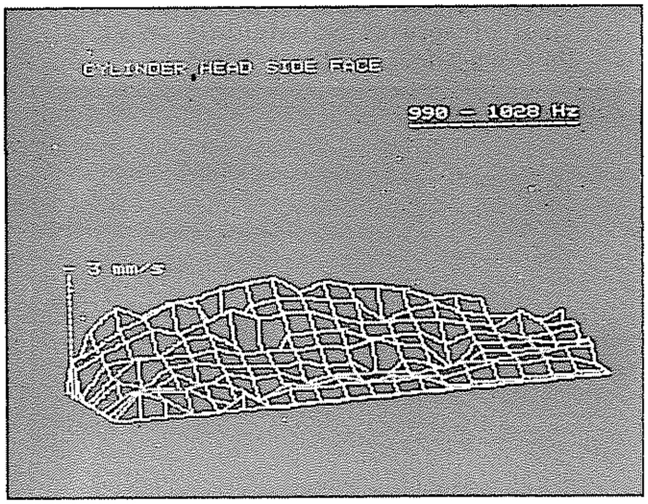

Fig.13: Vibration of the cylinder head at 1000 Hz: fundamental vibration of the edge zone to the valve corner

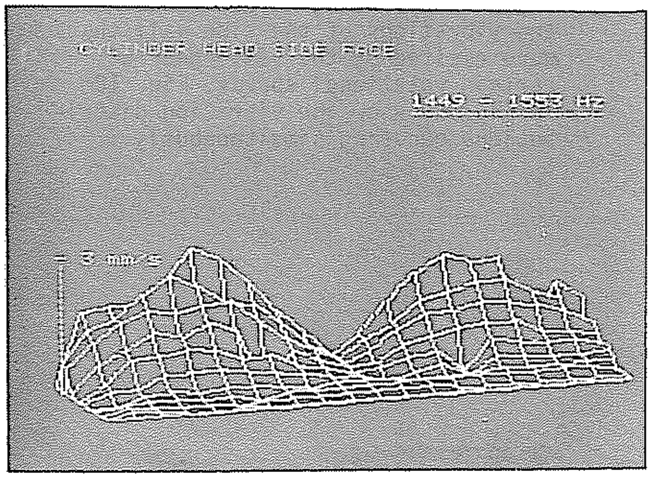

Fig.14: Vibration of the cylinder head at 1500 Hz: first harmonic

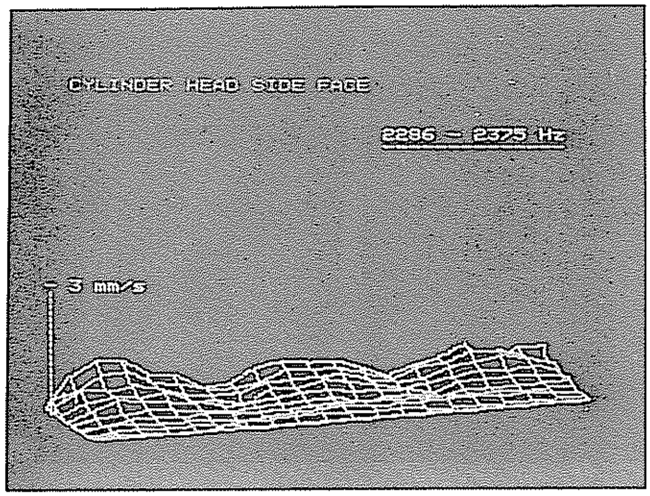

Fig.15: Vibration of the cylinder head at 2300 Hz: second harmonic, only weakly defined

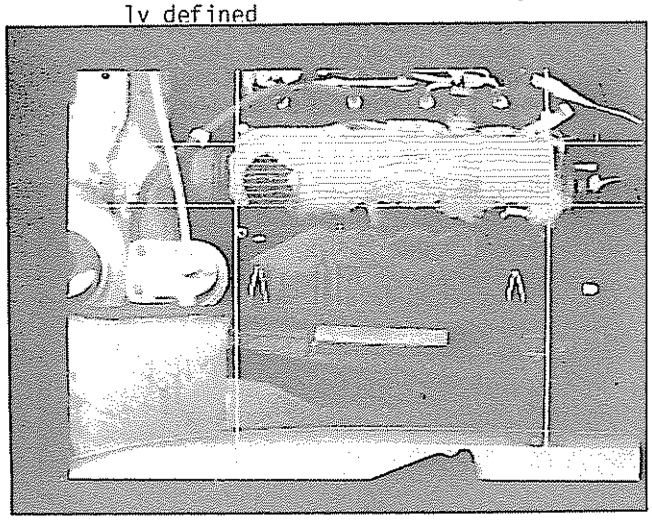

Fig.16: Valve cover of a diesel engine built into the vehicle. Set presentation of the vibration at 1000 Hz.

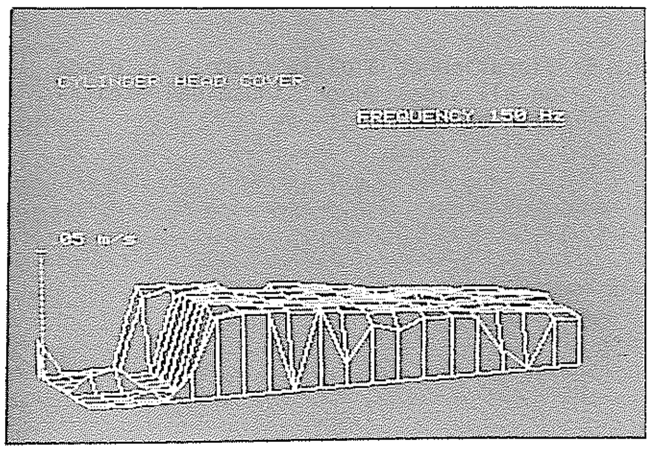

Fig.17: Movement of the valve corner at 150 Hz: whole-body movement of the engine

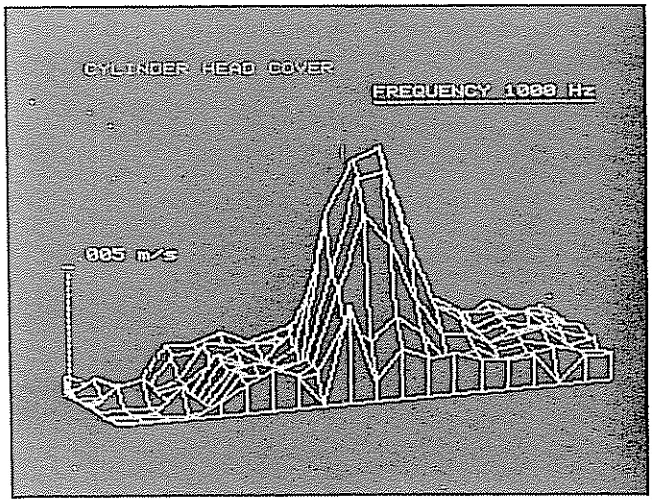

Fig. 18: Valve corner at 1000 Hz: free oscillation of a portion of the surface

SUMMARY

The method described can be used for evaluation of the vibrational behavior of an object in a minimum time. The vibrational data can be measured quickly and without contact in a great number of points and can be presented in graph form.

In comparison to other optical methods such as holography and speckle-interferometry, SOVAS is distinguished by the fact that self-excited objects can be examined in several ranges of frequency simultaneously, as well as components subject to sinusoidal and noise excitation. The process entails only a slight experimental expense and can be employed quickly. A disadvantage is the step-by-step acquisition of data: the vibration being investigated must be stationary for the duration of data acquisition - a maximum of a few minutes.

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