Brüel & Kjær

application notes

The Laser Velocity Transducer

Its Principles and Applications

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CAUTION

The Laser Velocity Transducer
Its Principles and Applications

by Mark Serridge, Brüel & Kjær

Introduction

There will always be occasions when it is impossible or undesirable to actually mount a vibration transducer onto a vibrating object. It is for those occasions that Brüel & Kjær in conjunction with The Institute of Sound and Vibration Research (ISVR) at Southampton University, England, has designed the Laser Velocity-Transducer Set Type 3544. Its simplicity of use and rugged construction means that the user need not concern himself with the state-of-the-art laser technology used during every measurement: to the user the Type 3544 simply represents a highly accurate and versatile vibration transducer.

The Laser Velocity Transducer Set Type 3544 consists of the Laser Velocity Transducer Type 8323 and the Power Supply Type 2815. By simply attaching a small piece of retroreflective tape to the surface of the vibrating object, and aiming the Type 8323 at it, vibration velocity and displacement at that point can be measured.

Type 3544 has evolved from the requirement of today's industries for a method of measuring vibration velocity *without* contacting the vibrating surface. For example, the loudspeaker industry has long needed to measure the vibration of light diaphragms without the mass-influence of an accelerometer; the aerospace and automobile industries are familiar with the problems of mounting accelerometers on very hot surfaces: these industries are also familiar with the time and cost of tapping holes and mounting accelerometers on an engine in a test-cell. In many industries, such as the power industry, there is often a need to measure lateral and axial vibrations of rotating shafts. The requirement for a transducer which could be simply pointed at *any* surface, and which told the vibration level at that surface has always been recognized.

With the development of the Type 3544 Brüel & Kjær has taken a basic physical principle - the Doppler Shift - and blended this with classical optical principles and more recent Laser technology, and successfully satisfied the requirements of the industries mentioned above. The Type 3544 is a fully portable vibration transducer which the user can simply point at a vibrating object and measure its vibration level.

How It Works

The heart of the Type 3544 is a low power (< 2 mW) Helium-Neon Laser. This produces the characteristic red

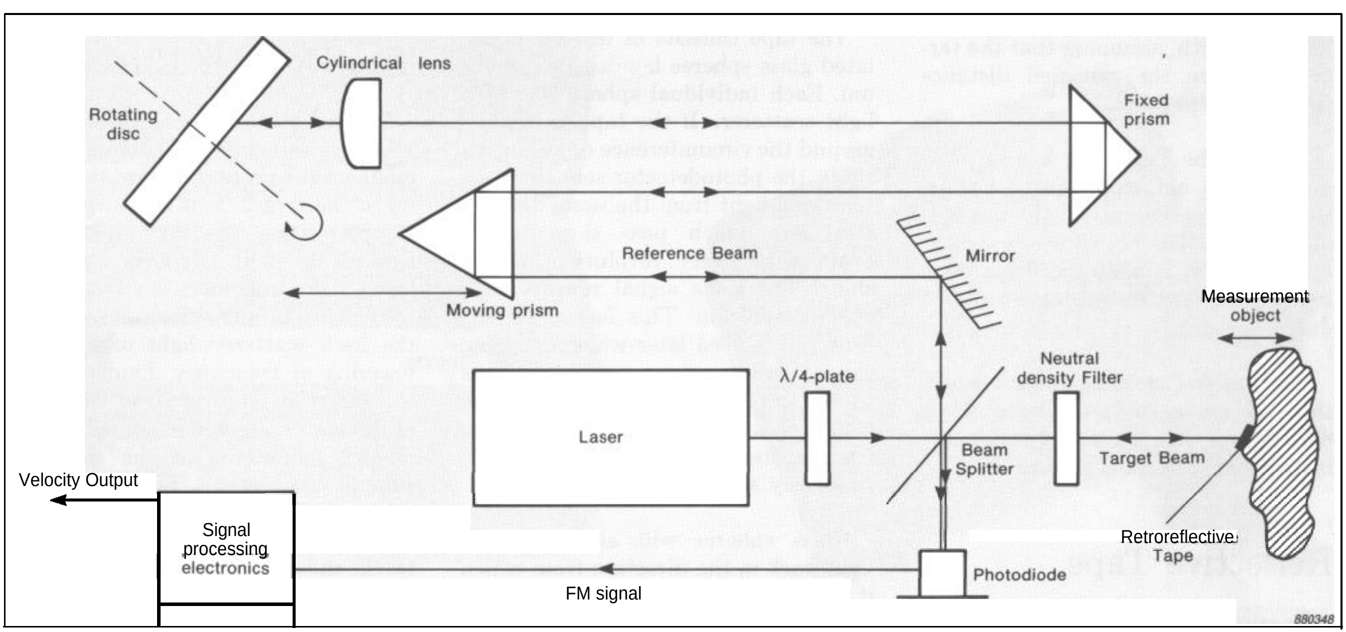

Fig. 1. The arrangement of the electronic and optical components within the Type 8323

light beam commonly associated with lasers. The arrangement of the principle components within the Type 8323 is shown in Fig.1.

The beam leaving the laser is split into two parts by using a beamsplitter. One of the beams is directed at the test object. The other beam (the ***reference beam)*** is directed at a rotating disc via one fixed and one moveable prism. Back scattered light from the rotating disc and the test object return on-axis with the incident beams and are mixed in the beamsplitter. This light is then directed towards a photodetector. The frequency tracking electronics after the photodetector first track the Doppler frequency shift caused by the vibrating surface and then produce a voltage proportional to the surface velocity in the direction of the beam.

Why Use Laser Light?

Laser light is used instead of any other because it has special properties, and in particular a property called ***temporal coherence.*** This means that we can divide and recombine the laser light such that a well defined phase relationship still exists between the beams upon recombination, even though they may have travelled different distances. The maximum path difference that can be tolerated before the phase relationship is destroyed is called the ***coherence length.*** The ***light level adjust*** control on the back of the Type 8323 varies the distance travelled by the reference beam within the instrument, and so ensures the path difference is not longer than the coherence length, assuming that the target is within the specified distance from the Type 8323.

Because the Type 8323 is a safe low power laser not employing focusing, the maximum distance to the target is about 0,8m. The advantage of a non-focused beam is that the Type 8323 requires no lengthy setting up procedure.

The neutral density filter ensures that the power output of the Type 8323 is less than lmw and brings the instrument into Safety Class 2.

Reflective Tape

Because the Type 8323 contains a low power laser without focusing lenses it is necessary to treat the target surface in some way to ensure sufficient back scattered intensity at the photodetector. The easiest solution is to apply a small piece of the supplied retroreflective tape (DU0164) to the point of measurement. The tape can withstand the extremely high temperatures found on hot exhaust systems as shown in Fig.2.

Fig.2 Retroreflective tape attached to the hot exhaust system of a car (photograph courtesy of The Ford Motor Company (UK) Ltd.)

The tape consists of densely populated glass spheres bonded in a medium. Each individual sphere acts as a light scatterer. If the tape is applied around the circumference of a rotating shaft, the photodetector sees the back scattered light from the same discrete scatterers which pass through the beam with every revolution of the shaft. The same signal repeats with every revolution. This fact is important and is used later when analyzing the pseudo-random noise sources within the instrument, since the Type 8323 has a rotating disc inside it to back scatter the reference beam and frequency shift it.

Glass spheres will always reflect light back in the direction from which it came. This means that the laser need not be perpendicularly incident on the surface in order to get back scattering into the Type 8323. It is always the velocity component in the direction of the beam which is measured.

An alternative to the tape is the paint (3M Type7210), which contains glass spheres. The principle is the same although it does not work as well as the tape.

The Doppler Effect

When light is scattered back from a vibrating target it will undergo a frequency shift proportional to the velocity of the target. This is known as the Doppler Effect. As the target moves towards the light source the back scattered light undergoes an increase in frequency; as the target moves away the back scattered light undergoes a lowering of frequency. Evidentally, if the target is vibrating, the frequency of the back scattered beam will be frequency modulated at the so called ***Doppler frequency.*** The Doppler frequency is directly proportional to the velocity of the target. Therefore, to track this Doppler frequency is to have a direct measure of the target's velocity ***relative*** to the motion of the light source.

The Reference Beam

The frequency of the back scattered light is of the order of 10^{15} Hz which is far too high in order to *directly* detect typical Doppler frequency modulations of the order of 10^6 Hz. So the first step to take is to mix the scattered light with a reference beam and direct the two at the photodetector, where they heterodyne. The current from the photodetector then becomes modulated at the Doppler frequency. So *indirectly* tracking the Doppler frequency like this produces a voltage proportional to the target velocity.

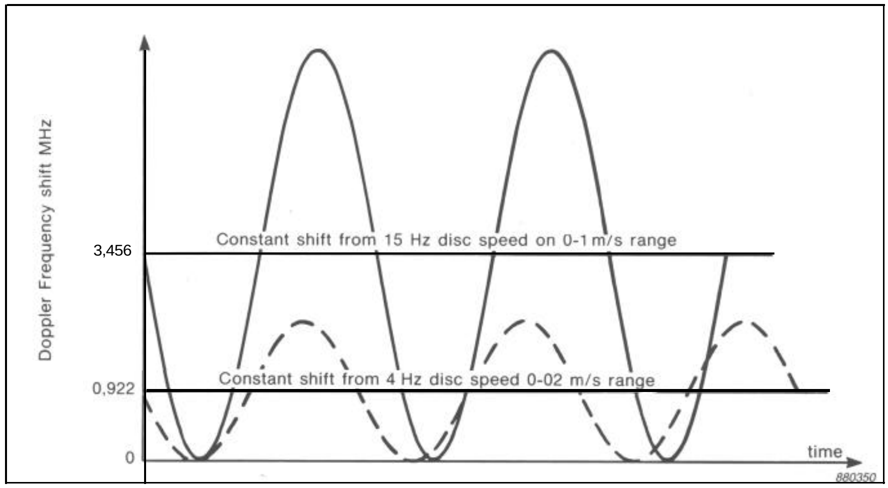

Fig.4. The frequency shift of the reference beam is obtained by using a rotating disc which can run at two speeds, enabling the selection of two different measurement ranges.

Frequency Shifting

The system described so far is of limited use in measuring vibration velocity. This is because vibrating surfaces during a vibration cycle have instants of zero velocity. When this happens we get no instantaneous Doppler shift and hence no voltage output. This leads to an ambiguity about the direction of the velocity; in vibration measurements, of course, the direction of the velocity is essential.

The problem is overcome by frequency shifting the reference beam by an amount of the order of one MHz. The Type 3544 achieves this by directing the reference beam at a reflective rotating disc placed at an angle to the reference beam. This adds a *constant* Doppler shift to the reference beam. This means that when the target object is stationary we still get an output at the photodetector, caused by the constant Doppler shift from the disc. The instrument can then be calibrated to give 0V at this frequency. Lower Doppler frequencies can then be made to give a negative voltage and higher Doppler frequencies to give a positive voltage. Now we can measure vibration velocities without direction ambiguities. This arrangement is easy to calibrate and self-aligning.

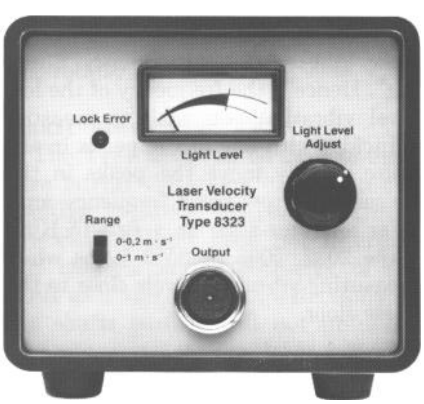

Fig.3 The rear panel of the Type 8323, showing the controls for "Range", and "Light level Adjust", together with the "Light Level" meter

The user can select two disc speeds - - 15Hz and 4Hz giving frequency shifts of 3,456MHz and 0,922 MHz. This has the effect of optimizing the dynamic range of the Type 3544, and is achieved by using the "Range" switch on the back of the Type 8323 (see Fig. 3). We can measure lower levels of vibration on the 0-0,2 m/s range.

Dynamic Range

The upper limit of the dynamic range is set by the maximum Doppler frequency which can be tracked. The lower limit is set by the smallest changes in Doppler frequency which can be detected by the frequency tracker.

Upper limit

The upper limit is quite easy to specify as it depends solely on the maximum frequency "swing" which can be accommodated by the frequency tracker. Fig. 4 illustrates this point. Large velocities produce frequency shifts which swing down close to the DC level. Consequently, the higher disc speed is used when we measure high velocities (the 1m/s range) because this gives more room for the Doppler swing, and the slower speed is used to measure lower velocities (the 0,2m/s range). The slower speed produces less Doppler shift of the reference beam. The Type 3544 has a maximum vibration velocity measurement capability of 1m/s peak.

An obvious advantage of the Type 3544 is that since it is not in contact with the target it cannot be damaged by measuring shocks.

Lower limit

The use of the rotating disc to produce a frequency shift has several advantages over alternative techniques such as Bragg cells and rotating diffraction gratings - cost and robustness being two major factors. Frequency tracking the Doppler frequency of the rotating disc produces a random noise pattern which repeats itself exactly with each revolution. A pseudo-random noise signal is produced with a spectrum as shown in Fig. 5. Hence the spectrum of the noise consists of peaks at the fundamental and harmonics of the rotation speed. The lower measurement limit of the instrument is limited by this noise pattern.

An effect called *Doppler frequency broadening* is associated with this noise floor.

Doppler Frequency Broadening

Ideally, when the Type 8323 is pointed at a stationary target a constant Doppler shift from the rotating disc should be measured by the detector. In practice, this is not quite the case, and the detector output varies in time with both amplitude and phase and a noise floor is created. (This is *not* caused by disc speed variations, which are negligible).

The term broadening refers to the widening of the Doppler frequency component. The Doppler frequency component from the disc appears as a peak up to several kHz wide. Consequently, low target velocities causing

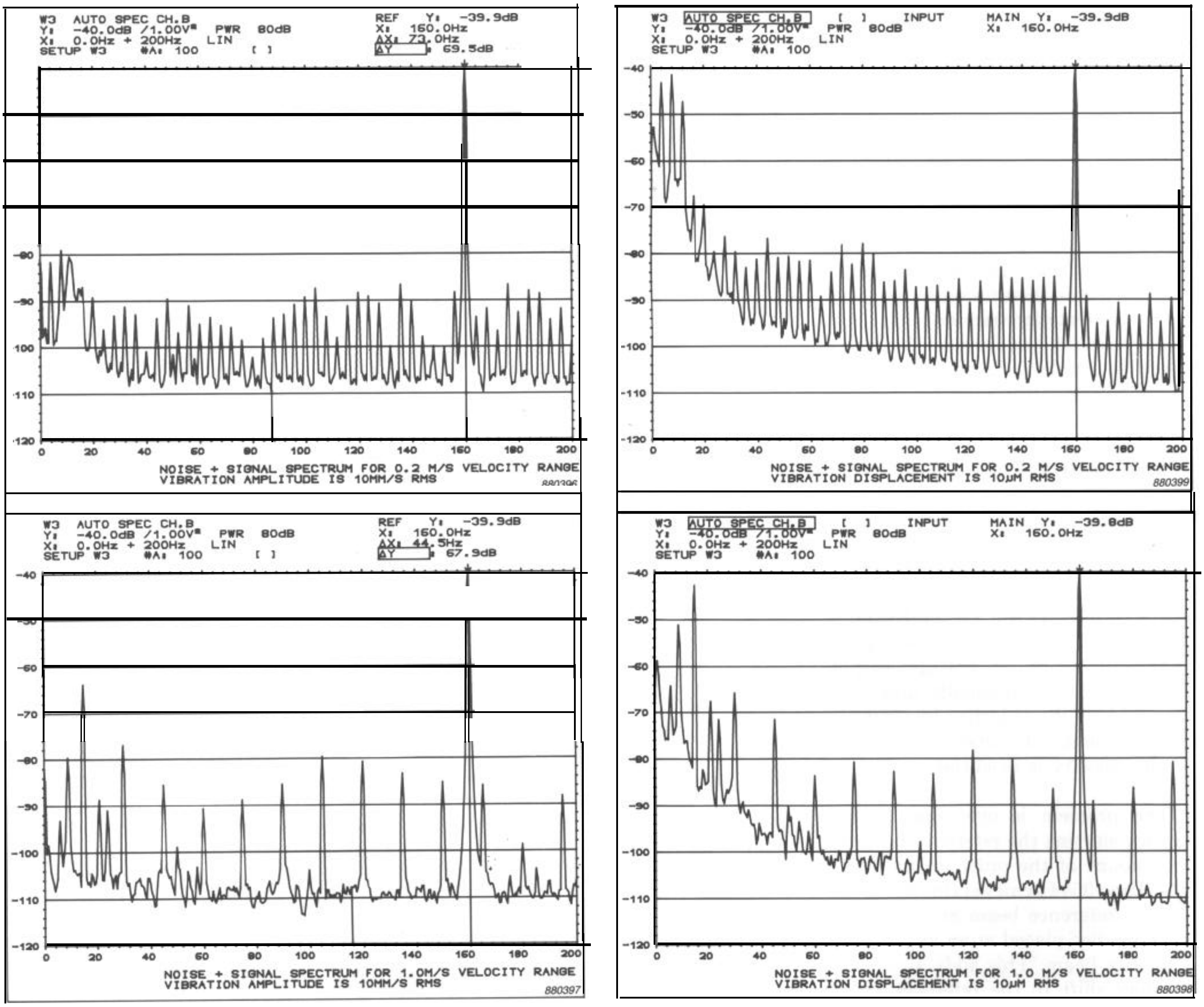

Fig.5. The noise spectra of the Type 3544 in 4 different modes. Top left is with 0,2m/s range (velocity). Top right is 0,2m/s range (displacement). Bottom left is 1 m/s range (velocity) and *bottom right is 1 m/s* range *(displacement). The component at 16OHz is the vibration from a* calibrated *vibration exciter giving lOmm/s. This is used* as an *indication of where the noise floor lies in terms of* actual velocity *and displacement amplitudes.*

Doppler shifts of similar magnitudes will go undetected by the frequency tracker.

There are several causes of broadening which are quite complex, but need only be mentioned briefly here;

When using a rotating disc to frequency shift the reference beam, the spatial distribution of scatterers repeats with each revolution. The fluctuations of the intensity on the photodetector therefore repeat with each revolution of the disc, and this is why the spectrum of the noise floor of the Type 3544 is that of the pseudorandom noise signal just described.

The laser spot impinges on a finite area on the disc and consequently there is a velocity gradient across the laser spot. All the particle scatterers present in the spot will not be moving at the same velocity and so will produce different Doppler shifts and broaden the Doppler frequency component of the reference beam.

Each particle scatterer on the disc only remains in the beam for a finite period of time, before the next particle moves in. Each particle produces a "burst" of scatter. Because we don't have a continuous signal at the photodetector, this time limitation causes a frequency broadening.

Two Rotating Disc Speeds

Because the noise floor of the instrument contains defined peaks, if we are interested in specific single frequency vibrations which do not coincide with the peaks, we can measure down to lower levels at all frequencies in between the peaks. To aid this the user can chose between two disc speeds as mentioned. This is achieved by using the "Range" switch on the back of the Type 8323 as described under the section "Frequency Shifting". Hence if the frequency of the low level vibration you wish to measure coincides with one of the peaks in the noise, simply move the peaks in the noise. A narrow band frequency analyzer analyzer such as a Brüel & Kjær Type 2032, 2033 or 2515 helps when measuring vibration levels close to the noise floor.

Rotating Target Surfaces

The ability of laser vibrometers to measure low level velocities is dependent on the target's surface velocity characteristics. If the particle scatterers within the laser beam spot only have a velocity in the direction of the incident laser beam then the laser speckle pattern which they form on the photodetector surface remains essentially stationary and no Doppler frequency broadenings occur.

However, if the scatterers *move* out of the beam and are replaced by others, such as when measuring on a rotating component, the speckle pattern on the photodetector will move and produce a broadening of the Doppler frequency associated with the shaft vibration we are trying to measure. This has the effect of significantly raising the level of the noise floor of laser vibrometers which employ Bragg Cells or other acousto-optic frequency shifting devices. However, for the Type 3544, the addition of a moving speckle pattern to the one already produced by the rotating disc has negligible effect on the lower limit and only further peaks associated with the rotational speed of the shaft will appear.

The speckle pattern produced by the target surface will also move on the photodetector if the particle scatterers "tilt" within the laser spot. In practice, and particularly at high amplitudes of vibration, all target surfaces have an inherent tilt associated with motion. This means that the practical advantages of Bragg Cell devices are lost, while the change in the noise floor of the Type 3544 is neglible in these circumstances.

Because changes to the lower measurement limit of the Type 3544 due to target rotation are slight, and depend on the rotational speed, it is not possible to accurately specify the noise floor of the instrument under such conditions and consequently the specifications of the instrument are only concerned with targets which do not rotate.

Shaft Vibrations

The Type 3544 can be used to measure lateral vibrations (unbalance) of rotating shafts. Unlike proximity probes, the laser does not interpret any changes in the geometry of the shaft as a vibration. Imperfections on the shafts surface will not influence the measurement. The laser will only detect vibrations of the centre of rotation of the shaft, in the direction of the laser beam. This may not be intuitively obvious. The following mathematical proof will help.

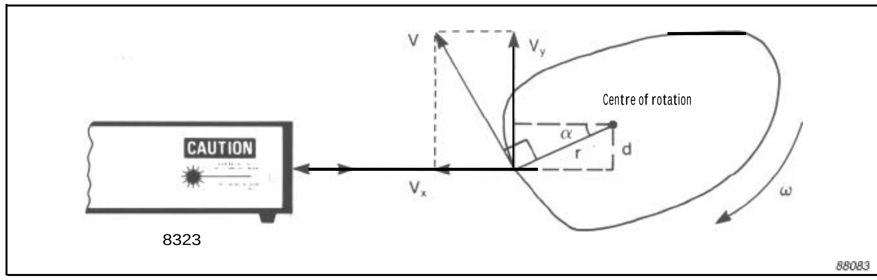

Fig.6. The Type 3544 does not interpret changes in *the distance to the surface of an irregularly shaped target* as a *vibration. When correctly* aimed, only **axial** *vibrations will be detected*

Consider a shaft with an irregular geometry, as shown in Fig.6. The shaft is rotating at an angular frequency of ω, corresponding to a tangential velocity of V at the point where the laser beam is incident, at a distance r from the axis of rotation, and at a vertical distance d below it.

The tangential velocity can be resolved into two components V_x and V_y, perpendicular to each other. The component in the direction of the beam, V_x, is then expressed as

$V_x = V \sin\alpha$ where α is as indicated.

Since $V = r\omega$, then .

$$V_x = r\omega \sin\alpha$$

r can also be expressed in terms of α and d, as

$$r = \frac{d}{\sin\alpha}$$

Therefore, $V_x = \dfrac{d\omega \sin\alpha}{\sin\alpha} = d\omega$

which is wholly independent of r.

Consequently, for a shaft with no axial vibration any Doppler shift in the laser beam is proportional only to the shaft rotation speed ω, which is a DC component, and the distance "off axis" of the laser beam. The laser does not interpret the changing distance to the target surface as a vibration.

A practical point results from this analysis. When making axial vibration measurements on rotating shafts it is important to ensure that d is zero or nearly zero by carefully aligning the laser beam so that it lies in a imaginary straight line passing through the centre of the shaft. This is important since the DC rotation component can often have considerably larger magnitude than the axial vibration itself, and in some cases may overload the Type 8323.

Frequency Range

Unlike the majority of vibration transducers, the Type 3544 does not suffer any electrodynamic frequency restrictions such as resonances and non-linearities of moving parts. There is a high frequency cut-off built into the electronics at 20 kHz. Besides that, if there is sufficient velocity at any frequency below 20 kHz, (including DC) it can be measured with the Type 3544. Otherwise, the frequency range of the Type 3544 is inextricably linked with its noise spectrum as can be seen in the specifications supplied with the Product Data Sheet, and the measurement range nomogram shown on the back page.

The Type 2815 contains an integrator to convert the velocity output of the Type 8323 into a displacement signal, enabling measurements of vibration displacements.

In velocity mode the Type 3544 is DC-coupled and hence measurements of DC velocities are possible. In displacement mode the Type 3544 has a 0,3Hz lower cut-off frequency. This is a result of the integration network.

To optimize the dynamic range of the instrument when making wide-band measurements, use is made of filters built into the Type 2815 Power Supply. The user can select between two wide-band frequency ranges in velocity mode (0 to 2 kHz and 0 to 20kHz). One frequency range is available in displacement mode (0,3Hz to 20 kHz).

Both a hand-held and a tripod-mountable instrument

The Type 3544 makes relative vibration measurements, i.e the vibration of the target relative to itself. Although no special expensive surface-table is required to make measurements, for the majority of applications the Type 3544 would be used mounted on its tripod supplied (UA0989). When low level, low frequency vibration measurements are required it it essential to mount the Type 3544 on the tripod.

When the instrument is used as a hand-held tool, spurious low frequency noise resulting from hand vibration, body-tremble and other environmental effects is introduced into the measurement at frequencies below 30Hz, thus raising the lowest detectable levels at these frequencies. Then the Type 3544 is less sensitive in the sub-30Hz range and unusable in the 0 to 10 Hz range. Consequently, the use of a high pass filter is recommended if wideband measurements are made using the Type 3544 as a handheld tool.

By using a magnet an accelerometer can be attached to the back plate of the Type 8323. By measuring the vibration of the Type 8323 in this way it is possible to obtain the absolute level of the vibration from the relative measurement given by the Type 8323. However, under normal circumstances with the the Type 8323 standing on solid ground, its own vibrations are negligible.

Operating Distance

For optimum performance the Type 8323 should be placed between 20 and 80cm from the target. Within this range it is possible to optimize the measurement and improve the coherence by varying the distance travelled by the reference beam. This is achieved by mechanically repositioning a mirror inside via the "Light Level Adjust" control on the rear panel as described earlier. A simple meter indicates the coherence obtained.

Type 3544 is Simple to Use

The Type 3544 marks the advent of easy to use laser measurement technology, being extremely simple and fast to operate.

The Type 3544 consists of two parts; the velocity transducer Type 8323 containing the laser (and its associated electronics), and its Power Supply Type 2815 (containing the filters and integration networks). The two are connected by the cable AO0308. This cable carries both power and velocity signals. Type 2815 gives a calibrated voltage output proportional to velocity or displacement. This can be fed into a wide variety of analysis instrumentation.

The user simply attaches the retro-reflective tape to the target and points the laser at it to obtain either a wide-band vibration measurement on a voltmeter or narrow-band information on a frequency analyzer.

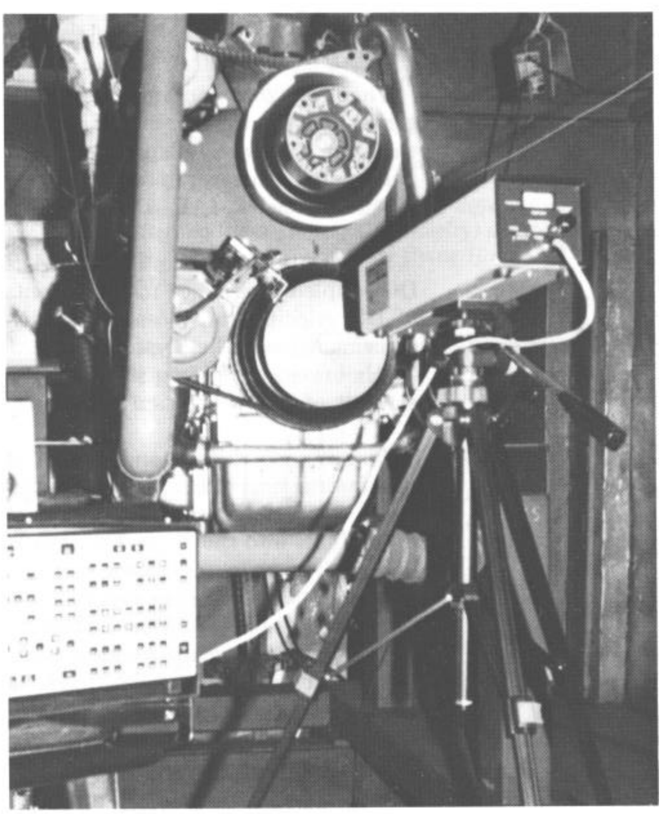

Fig.7. The Type 3544 can be used to measure the vibration of rotating surfaces. In this example the axial vibration drive shaft of an engine is being investigated (photograph courtesy of the Automotive Design Advisory Unit, Southampton, England)

Fig.8. The Type 8323 is simple to operate. It is shown here mounted on the tripod supplied

The angled mirror Type UA0965 can be attached to the front of the Type 8323. This turns the beam through 90° thus facilitating measurements on targets in awkward locations.

Portability

A unique concept in the deisgn of the Type 3544 is its portability, being compact and battery powered.

The Type 3544 and all its accessories is easily carried or wheeled along in its sturdy protective carrying case, giving a total weight of 21 kg. The Type 2815 accepts the battery box Type QB0040, which contains 12 1,2V rechargeable batteries. These can be recharged using the charger Type ZG0166. The Type 3544 can also be powered from any suitable +12 to + 15 V power supply with a 4A capability. The charge time for fully depleted batteries is 20 hours. Charging is possible while the instrument is in use.

Type 3544 is Safe

The Type 3544 complies with Safety Class 2 of British Standard BS 4803 - Radiation Safety of Laser Products and Systems, IEC 825, and ANSI

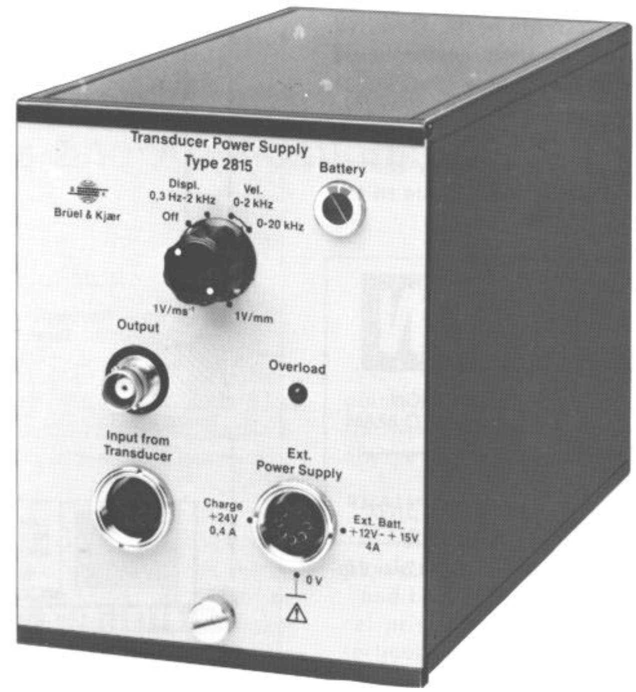

Fig. 9. Portability is offered via The Power Supply Type 2815 containing batteries for the Type 8323, integration networks and wide-band filters

Fig.10. The Type 3544 comes complete with a sturdy carrying case which can contain the Type 8323, the Type 8315 and all the accessories including the tripod and spare battery box

Z136.1 (1980). Class 2 lasers such as the Type 3544 have a target beam power of less than 1 mW and are "safe for accidental momentary viewing". This means that the user should not stare directly into the beam. However, if by accident the laser beam should directly enter the eye, normal reflex blinking actions will be sufficient to protect the lens and retina from all possible injury. It is perfectly safe to expose any other human tissue to the laser light.

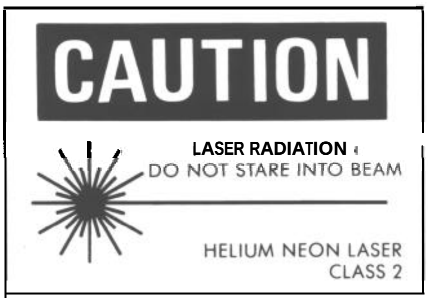

Fig. 11 The Type 3544 is a Safety Class 2 laser device

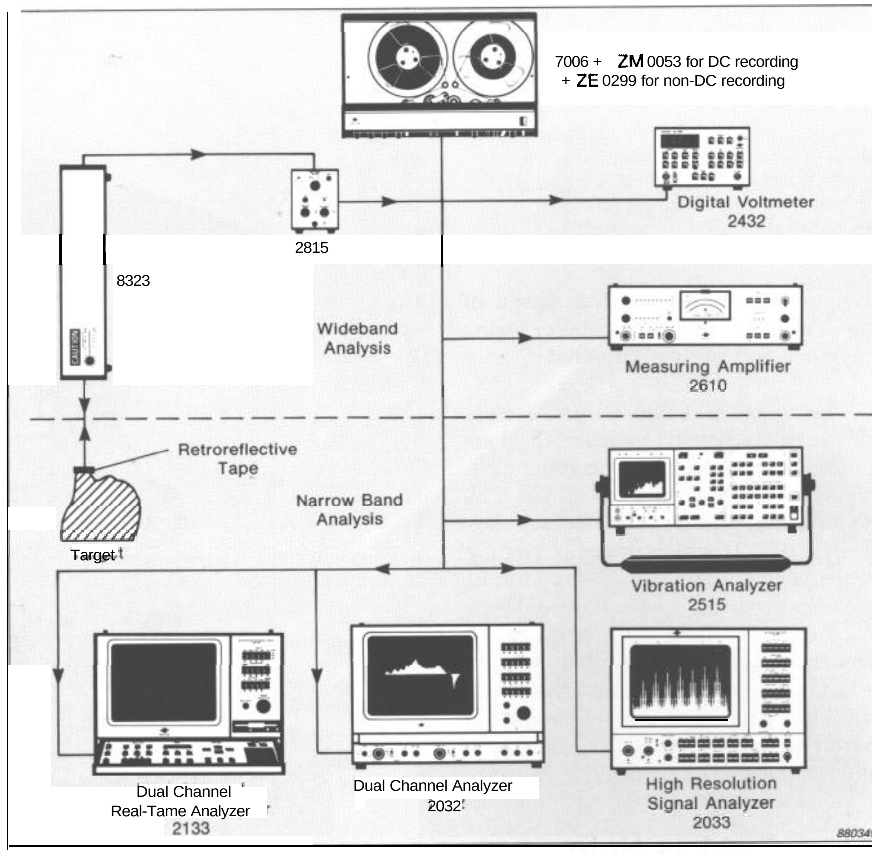

Fig.12. Brüel & Kjær offer a comprehensive range of both wideband and narrowband analysis equipment to follow the Type 3544

Use With Other Instruments

The output of the Type 2815 is a voltage-time signal proportional to the surface velocity. For wideband measurements this signal can be fed into a voltmeter or measuring amplifier. For frequency analysis the output can be fed into a digital or analogue analyzer. Brüel & Kjær manufacture a comprehensive range of vibration measurement and analysis equipment for every application. Some suggested instrumentation setups are shown in Fig. 12.

Application Areas

The Type 3544 is not designed to replace the accelerometer as the everyday all-purpose vibration transducer. Instead the Type 2544 is designed for use in all occasions where it an accelerometer cannot be used. Typical applications are measurements on;

Light structures, hot structures, inaccesible parts, surfaces which must not be marked, very small surfaces, high voltage surfaces, radioactive sur-

Fig. 13. Measuring differential vibration on a tyre as it spins (photograph courtesy of The Ford Motor Company (UK) Ltd.)

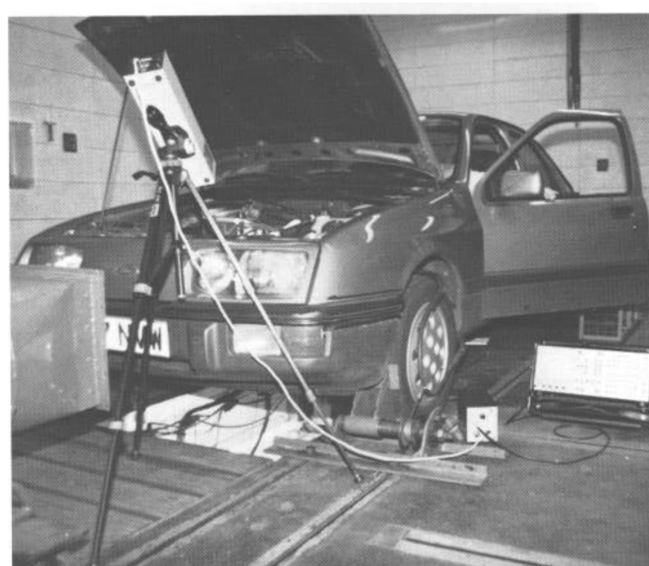

Fig.14. Measuring the vibration of a rubber airhose in an engine (photograph courtesy of The Ford Motor Company (UK) Ltd.)

faces, living tissue, wet surfaces, rotating surfaces (sides or ends of shafts), machines which would otherwise have to be stopped to attach an accelerometer (no down-time required if paint is applied to the rotating shaft), continuous surfaces moving with a DC velocity (e.g. measurement of the speed of a rotating disc), shock measurements etc...

Such measurements may often be required in the automobile, aerospace, power, and loudspeaker industries, as examples.

Further Reading

[l] The Laser Vibrometer - A Portable Instrument, Neil Halliwell, Journal of Sound and Vibration, 1986, 107 (3), pp 471-85

[2] Vibration Measurement using Laser Technology, ISVR/SIRA Course Notes, available from SIRA Ltd., South Hill, Kent, England

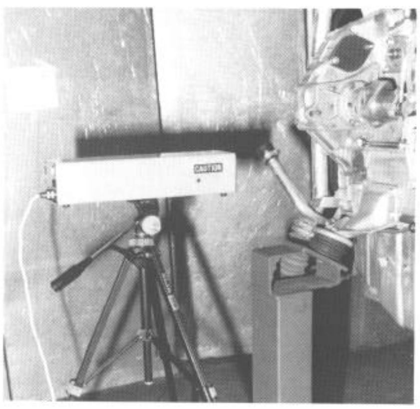

Fig.16. Measuring unbalance of a flywheel in a diesel engine (photograph courtesy of the Automotiue Design Advisory Unit, Southampton, England)

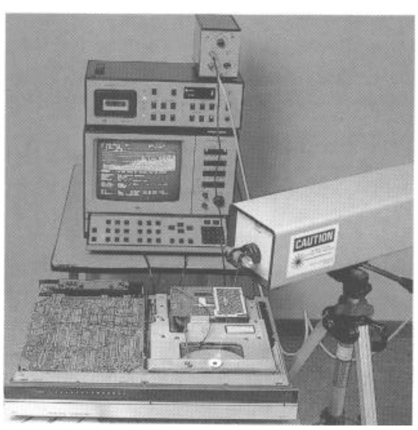

Fig. 17 Investigating the vibration transmission characteristics of a Compact Disc player mounted on a vibration exciter (photograph courtesy of Bang& Olufsen A/S Denmark)

Fig.15. Making an Operational Deflection Shape Measurement on an exhaust pipe by using two lasers (photograph courtesy of The Ford Motor Company (UK) Ltd

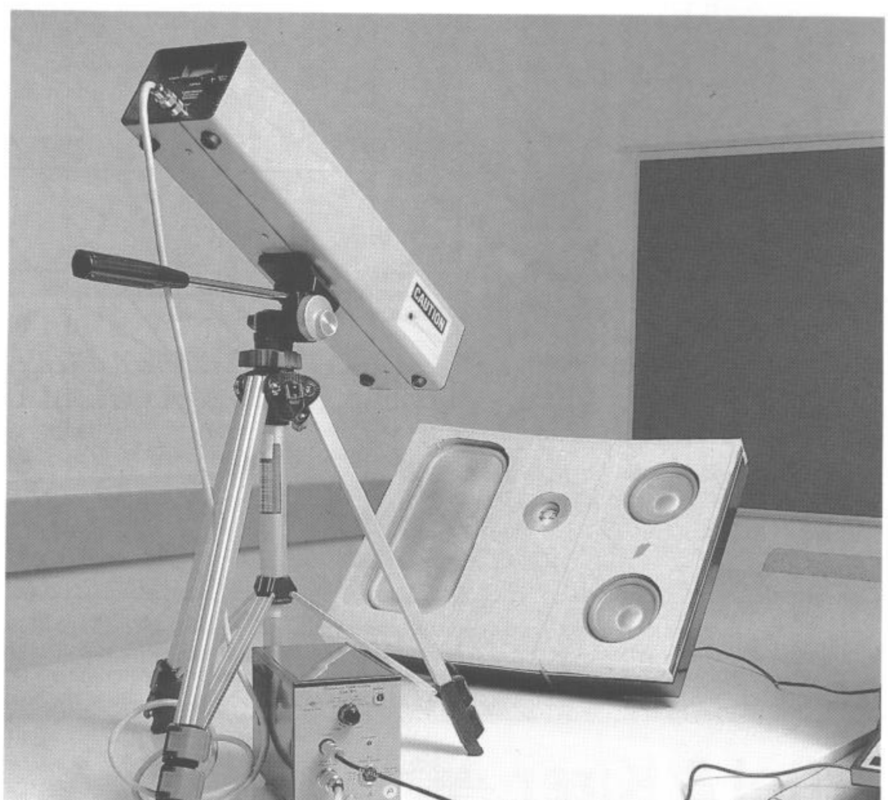

Fig.18. Measuring the vibration of a tweeter diaphragm (photograph courtesy of Bang & Olufsen A/S Denmark)

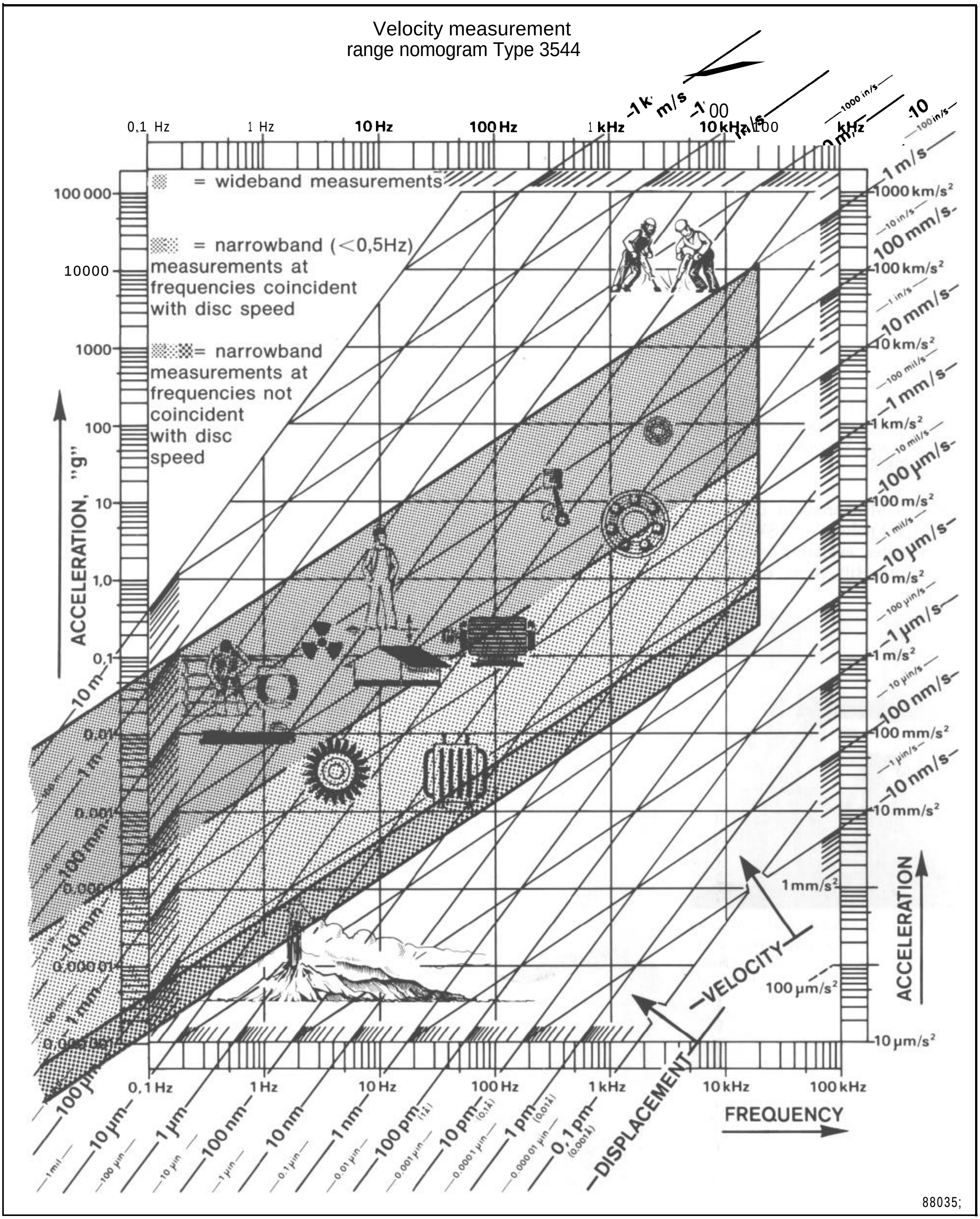

Fig.19 The frequency and dynamic measurement ranges (in *velocity mode) of the Type 3544, indicating the possibilities* when *the* output *of the Type 2815 is fed either into wideband analyzers such as voltmeters and* measuring *amplifiers, or into narrowband* analyzers *such FFTs. Two areas are shown for* narrowband analysis, *depending on whether the frequencies of interest correspond to harmonics resulting from the two rotating disc frequencies (4Hz and 15 Hz). The upper limit is the peak level, whereas the lower limits are RMS levels*

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