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FIBRE-OPTIC VIBRATION PROBE

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Abstract

A practical all-fibre laser vibrometer is described. The design has been optimised for hand-held use and incorporates a frequency-scanned laser-diode and a single-mode optical-fibre coupler. The vibration information is extracted by a pseudo-heterodyne technique.

Introduction

Laser-Doppler velocimetry (LDV) is now a well-established technique for non-contact measurement of surface vibration[1,2]. The principle relies on scattering light from a surface and observing the Doppler shift in frequency which occurs when the surface moves. In order to determine the direction of motion, it is necessary to optically heterodyne the scattered light with a frequency-shifted reference beam to provide a carrier frequency which is then frequency modulated by the surface motion.

At least one commercial instrument is available[2] employing a Bragg cell to frequency shift the reference beam. However, other more convenient forms of heterodyne signal processing have recently been developed. For example, Jackson et al[3] produced the frequency-shifted reference by ramped phase-modulation using a semiconductor laser diode, whilst Lewin et al[4] used sinusoidal modulation of a fibre wrapped around a piezoelectric crystal. These schemes have produced carrier frequencies up to 10^4Hz, which severely limits the highest vibration velocity which can be measured.

In this letter we describe a fibre-optic vibrometer which avoids the use of a separate frequency-shifting device and also provides a convenient hand-held fibre probe.

Fibre Vibrometer Design

The vibrometer design utilises the pseudo-heterodyne scheme[4] to obtain frequency-shifting. A laser-diode was sinusoidally driven at 1.05MHz to give optical phase modulation, thus avoiding linearity problems associated with ramped phase-modulation[3], whilst generating a frequency-shift of sufficient magnitude to measure large vibrations ($\sim 10^{-1}$ ms^{-1}).

A diagram of the vibrometer is shown in Figure 1. The laser output is launched into one port of a 4-port single-mode fibre coupler which has one of its output ports index-matched, whilst collimated light from the other port illuminates the target surface. Scattered light re-enters the fibre and is directed via the 4-port coupler to the detector, where it is mixed with a reflected reference-signal obtained from the fibre-Selfoc interface. The arrangement ensures that the fibre path is common to both signal and reference, thus ensuring that the probe is insensitive to environmental disturbances. This factor is crucial in the design of a practical engineering instrument.

Theory

A change in drive current to a laser diode produces a frequency shift[5] in the output radiation (~1.0 GHz/mA). Thus sinusoidally modulating the laser drive current at a frequency ω_m sweeps the lasing frequency ν by an amount

$$\nu = \nu_0 + \Delta\nu \sin \omega_m t \qquad (1)$$

where ν_0 is the mean laser frequency and $\Delta\nu$ is the peak frequency shift. The reflected light from the end face of the fibre and the scattered light from the target surface interfere at the detector to produce an intensity which is modulated by their phase difference. If ℓ is the fibre-end to target distance and is large ($\ell > 50$mm) such that amplitude modulation of the laser at frequency ω_m can be ignored, the current output from the detector i(t) is

$$i(t) = \beta(I' + K\cos(\phi_m \sin\omega_m t + \phi_T)) \;, \qquad (2)$$

where β is a constant relating to optical power and detector sensitivity, K is a measure of the scattered-signal amplitude (the "fringe visibility"),

$$\phi_m = 4\pi\ell \frac{\Delta\nu}{c} \text{ and } \phi_T = 4\pi\ \ell\ \frac{\nu_0}{c} \qquad (3)$$

Expanding in terms of Bessel functions we can write

$$i(t) = \beta(1 + K\{J_0(\phi_m) + 2\sum_{n=1}^{\infty} J_{2n}(\phi_m)\cos 2n\omega_m t\}\cos\phi_T$$

$$- K\{2\sum_{n=0}^{\infty} J_{2n+1}(\phi_m)\sin(2n+1)\omega_m t\}\sin\phi_T) \ . \qquad (4)$$

It has been demonstrated[6] that a signal of this form can be demodulated by mixing with a square wave at the fundamental frequency ω_m, and maintaining the phase excursion, $\phi_m = 2.82$ rad. The latter is obtained by controlling the laser drive $\Delta\nu$.

After square-wave mixing, the resultant signal is bandpass filtered at a frequency $2\omega_m$ to give

$$i(t)_{2\omega_m} = \beta K J_2(\phi_m)\cos(2\omega_m t - \phi_T) \qquad (5)$$

Here the optical phase shift ϕ_T has been transposed to a low-frequency electronic phase-shift. Thus frequency demodulation gives the surface velocity according to

$$\frac{d\phi_T}{dt} = \frac{4\pi\nu_0}{c} \frac{d\ell}{dt} \qquad (6)$$

Practical system

Figure 1 shows the fibre vibrometer probe. Signals at 1.05, 2.1 and 4.2 MHz were generated and the 1.05 MHz signal used to modulate the laser through an AGC amplifier. The detector output (equation (4)) was mixed with the 2.1 and 4.2

MHz signals in two parallel operational multipliers. Their respective outputs were low-pass filtered to obtain $J_2(\phi_m)\cos\phi_T$ and $J_4(\phi_m)\cos\phi_T$. The ratio $J_2(\phi_m)/J_4(\phi_m)$ was obtained and used to develop a control voltage to the AGC amplifier, thus automatically controlling the frequency excursion of the laser $\Delta\nu$ to give $\phi_m = 2.82$ rad. This compensates for variations between laser diodes temperature effects and the distance from the probe to the vibrating surface.

To extract the vibration information, the detector output was synchronously gated at frequency ω_m, using an analogue switch. The switched output was fed to a frequency tracker which extracted the second harmonic of the signal (eqn. (5)). The tracker measures $d\phi_T/dt$ and thus provide an output voltage proportional to surface velocity.

Results

Figure 2 shows a typical comparison between measurements of surface vibration made using the fibre vibrometer and a commercial accelerometer. The surface of the two measurements was vibrated at 132 Hz with a shaker. The two measurements are in excellent agreement. The noise floor from the fibre vibrometer is marginally higher at ~ -105dB re. 1ms^{-1} rms, compared to 110 dB re. 1ms^{-1} rms for the accelerometer. Moreover, the fibre vibrometer shows some low-frequency mains feedthrough at 50, 100, 150 and 200 Hz. Circuit modifications are in hand to improve both these areas.

Vibration frequencies up to 20KHz have been measured, restricted only by the frequency tracker. Figure 3 demonstrates the large velocities measurable with the vibrometer, in fact the maximum was excellent at $\pm 0.2\text{ms}^{-1}$, the limit being the presence of sideband frequencies associated with the odd harmonics ω_m and $3\omega_m$. If required, an even larger velocity range could be obtained by increasing the laser modulation frequency by several tens of MHz.

The fibre vibrometer was designed to have a fibre end to target range between 50 and 300mm. Again, this can be extended by circuit modifications.

Conclusion

We have developed a practical fibre-optic vibrometer which utilises the pseudo-heterodyne scheme to avoid the use of a separate frequency-shifter. The vibrometer is ideally suited to hand-held machine vibration analysis, since it is insensitive to external vibrations, robust and lightweight, uses inexpensive components and allows access to difficult targets. Dynamic range is already close to that obtainable by other LDV methods and further improvements are expected with some elementary refinements.

Acknowledgements

Thanks are due to S.B. Poole for helpful discussions. The work was supported by the UK Science and Engineering Research Council and Readership was provided by Pirelli General plc.

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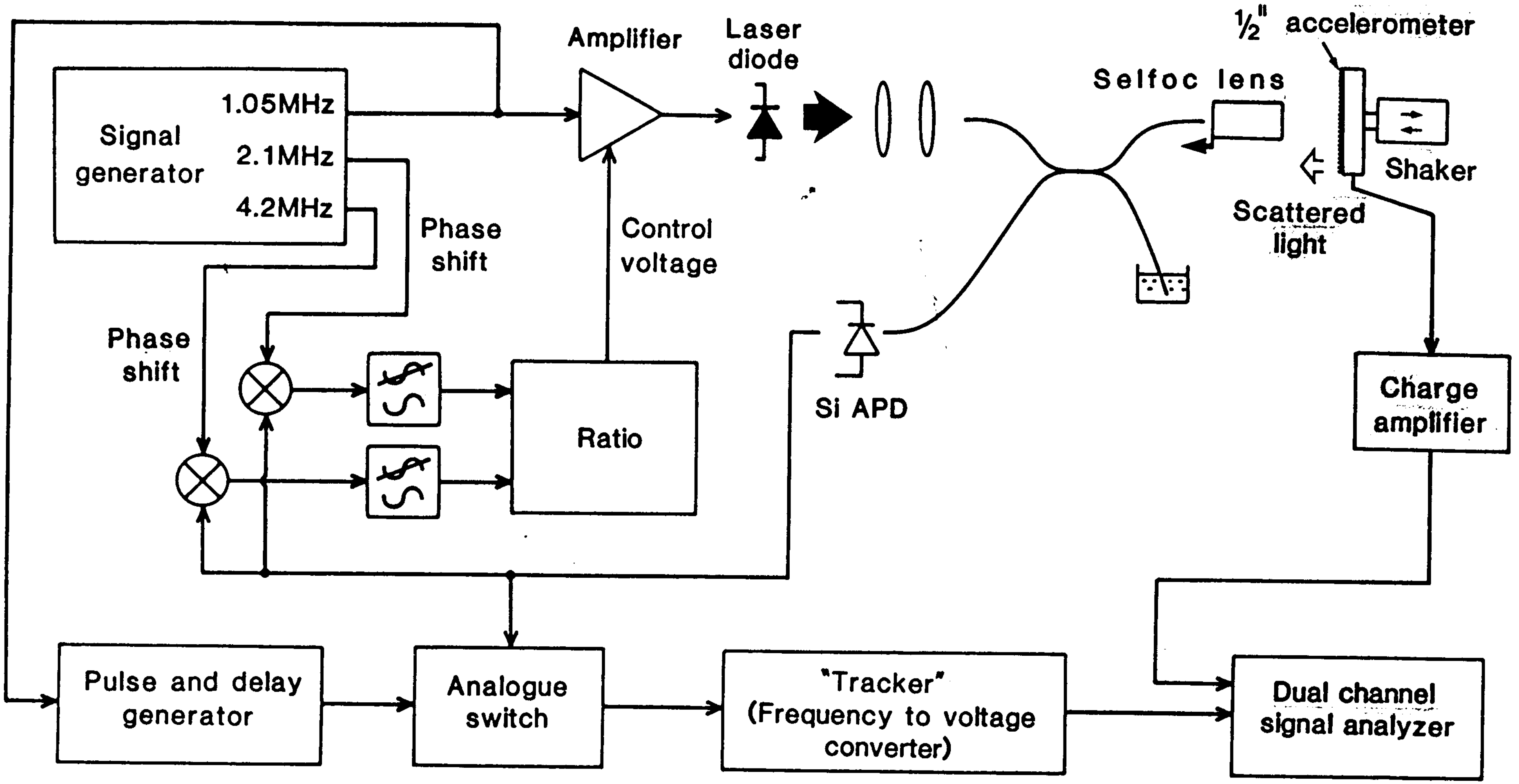
Figure Captions

Figure 1 Practical fibre-vibrometer.

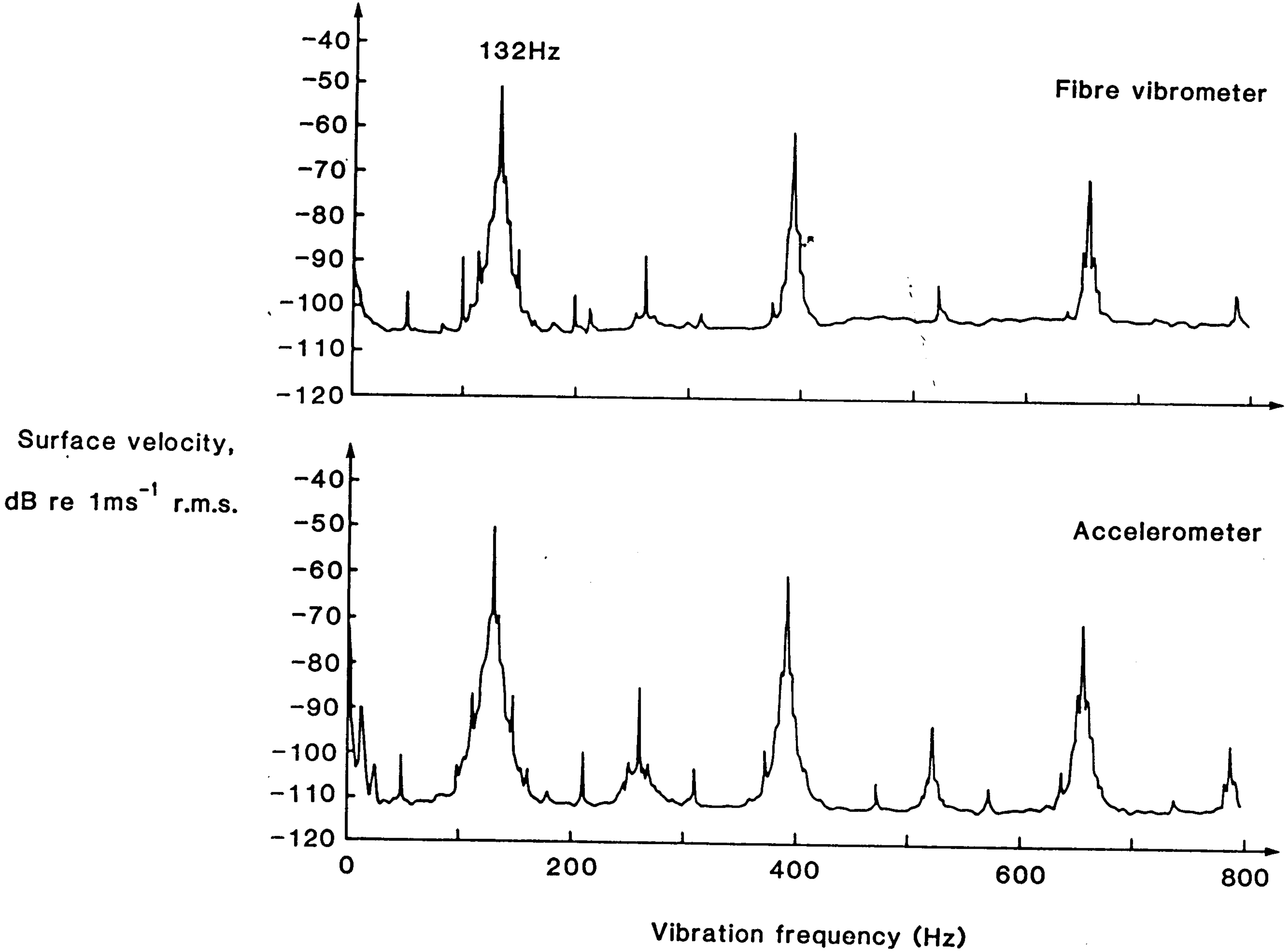
Figure 2 Spectral plot of test-surface velocity obtained using the fibre-vibrometer compared with that given by an accelerometer.

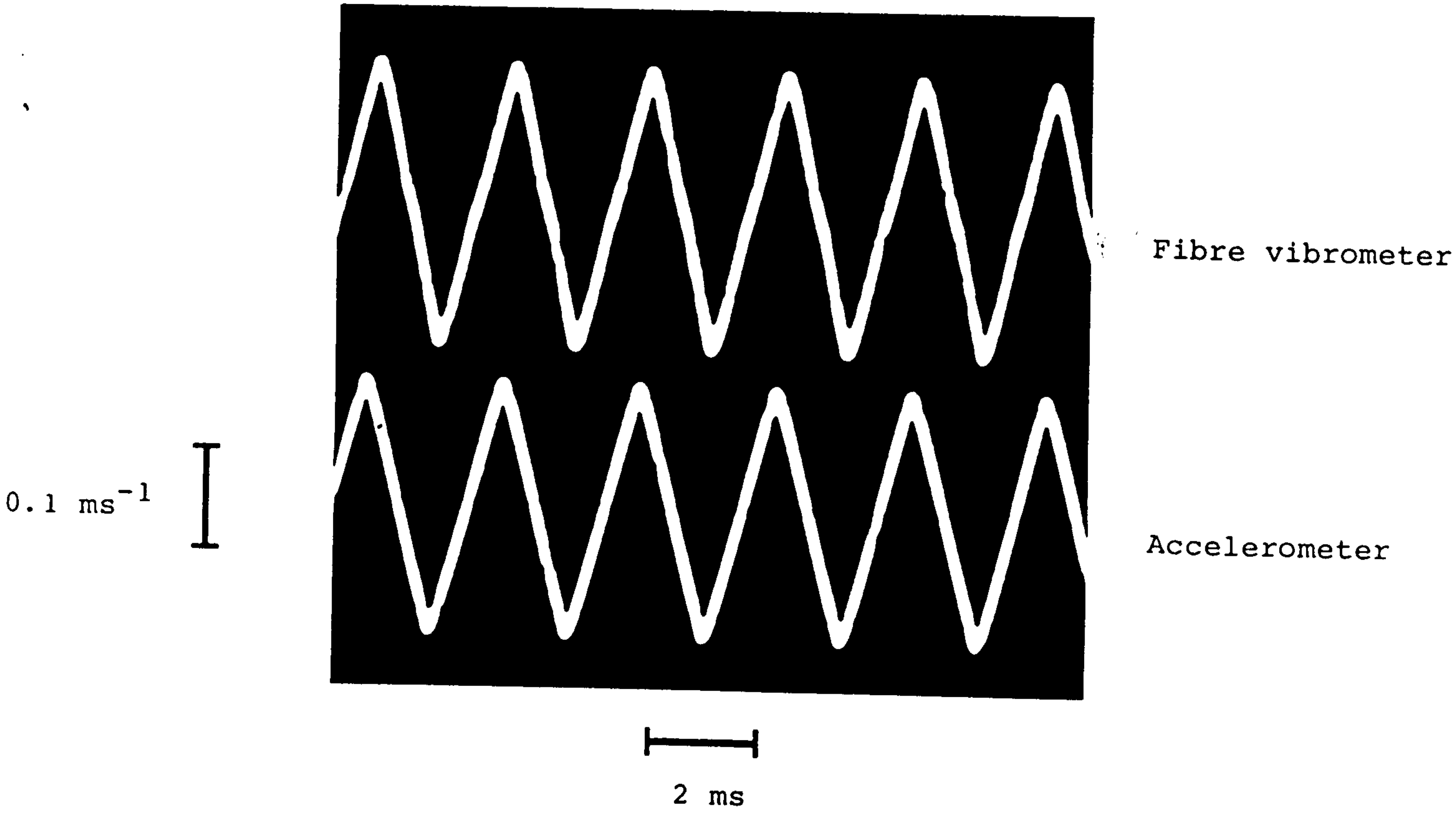
Figure 3 Output traces of test-surface velocity obtained using the two devices. The trace shows the large velocities measurable (0.29ms^{-1} p-p).

Fig 1



½" accelerometer
Amplifier
Laser diode
Selfoc lens
Shaker
Scattered light
Signal generator
1.05MHz
2.1MHz
4.2MHz
Phase shift
Control voltage
Phase shift
Ratio
Si APD
Charge amplifier
Pulse and delay generator
Analogue switch
"Tracker" (Frequency to voltage converter)
Dual channel signal analyzer


132Hz
Fibre vibrometer
Accelerometer
Surface velocity,
dB re 1ms^{-1} r.m.s.
-40
-50
-60
-70
-80
-90
-100
-110
-120
0
200
400
600
800
Vibration frequency (Hz)


Fibre vibrometer
Accelerometer
0.1 ms^{-1}
2 ms