Sensing tyre pressure, damper condition and wheel balance from vibration measurements

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Abstract: The majority of disturbance and control forces affecting a vehicle are transmitted through the tyre–ground interfaces. For optimum performance, components at each wheel station should be regularly inspected and maintained. Failure to maintain tyre pressures at correct levels results in increased tyre wear, increased fuel consumption, reduced ride comfort and degradation of vehicle handling. Worn dampers also reduce ride comfort and are detrimental to handling. Unbalanced wheels lead to vibration and wear in steering linkages.

A system is proposed which will monitor these parameters while the vehicle is being driven in the normal way. The system is based upon measuring the vertical vibration at each wheel/axle station. Subsequent signal processing enables a dashboard indication of tyre pressures, damper effectiveness and wheel unbalance to be made available to the driver.

Keywords: automotive, condition monitoring, tyres, dampers, wheel balance

NOTATION

A	amplitude of resonant peak in spectrum (g)
c	damping constant (N s/m)
f	frequency (Hz)
f_0	centre frequency of resonant peak in spectrum (Hz)
k_s	suspension stiffness (N/m)
k_t	tyre stiffness (N/m)
m_s	sprung mass (kg)
m_{us}	unsprung mass (kg)
p	tyre pressure (bar)
Q	damping parameter
r	tyre rolling radius (m)
v	vehicle velocity (m/s)
x_g	relative ground displacement (m)
x_s	sprung mass displacement (m)
x_{us}	unsprung mass displacement (m)
X_s	amplitude of vibration of sprung mass (m)
X_{us}	amplitude of vibration of unsprung mass (m)
Δf	bandwidth at half power points
ζ	damping factor
ω	natural frequency (rad/s)

1 INTRODUCTION

The occurrence of a puncture in a tyre is at best inconvenient and at worst potentially fatal. Despite great advances in tyre technology over the past 100 years, the prospect of a puncture is still a fact of life for the modern motorist. In the United Kingdom figures suggest that on average a motorist will experience one puncture every 32–40 000 km (20–25 000 miles) (**1**). Further research shows that approximately 50 per cent of punctures are discovered when the vehicle is stationary but as many as 25 per cent occur during driving and result in potentially dangerous situations. The problems associated with a 'blow-out' are obvious and fortunately this type of occurrence is becoming less common. However, the more usual scenario of a sharp object piercing the tyre followed by a slow deflation can be equally dangerous.

The danger arises due to the substantial changes in handling behaviour that occur when a vehicle is operated on an underinflated tyre, resulting in the increased chance of being involved in a serious accident. Investigations have shown that nails or sharp objects can puncture and remain in tyres for 300 km or more. During this time the tyre generally deflates slowly resulting in a gradual deterioration in handling. This is unlikely to be noticed by the average motorist unless involved in an emergency manoeuvre and then it might be too late.

Considerable effort has been applied by tyre manufacturers over the years to this problem. Developments have included puncture resisting tyres, self-sealing tyres and run-flat tyres. Despite some ingenious ideas, few of the

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developments have yet found their way into the mass market for a variety of reasons.

As well as increased danger for drivers and other road users, running on tyres which are underinflated increases the rolling resistance with a subsequent reduction in vehicle performance (acceleration and top speed) and a corresponding increase in fuel consumption rate. The reduced pressure also causes increased tyre wear and it has been found that a 20 per cent reduction in tyre pressure results in a 30–40 per cent reduction in tyre life. A further penalty deriving from front tyres which are underinflated is heavier steering resulting in increased wear of steering links and a sluggish steering response.

As well as tyre pressure, the condition of the damper at each wheel is important in ensuring safe handling behaviour. There appears to be no quantitative means of testing damper quality of vehicles other than 'bouncing' each corner and observing the ensuing oscillation. Deciding whether the damper is satisfactory or that it should be replaced then becomes a very subjective decision.

Wheel out of balance is another problem which the average motorist generally will not be aware of until the problem becomes severe. By this time steering joints and tyres will have been subjected to increased rates of wear.

It would therefore be advantageous for the driver to be given early warning of such problems by reliable on-board instrumentation. The problem of detecting tyre pressure changes has received considerable attention in recent years. One of the earliest approaches was to take a pressure tapping through the wheel and axle assembly which then allowed conventional pressure transducers to be mounted on the vehicle. An added advantage of this design was the ability to inflate or deflate the tyres while driving, which was helpful when travelling over mixed terrain, e.g. road/mud/snow. The main drawback was the necessity to provide a seal between rotating and non-rotating components and this fact has restricted the application of this approach to specialized vehicles involved in this type of operation. A more recent approach (**2**) has resulted in the development of a piston type pressure transducer mounted on each wheel of the vehicle. Changes in pressure are detected by a Hall effect probe mounted on the axle, sensing changes in piston position relative to a datum. The device is relatively inexpensive but long-term reliability in the harsh environment found under wheel arches remains to be proved. Telemetry (**3**) has been used to provide power to wheel-mounted transducers and to receive signals for on-board display but there is no evidence of the system being widely used, presumably due to high costs and limited reliability. Systems have recently been developed with pressure transducers inside the tyre volume, the signals being transmitted at radio frequencies. The power for these devices is provided by batteries (**4**, **5**). Battery lives of 10 years are being claimed by the manufacturers but long-term reliability remains to be proved on a commercial scale.

A system based on sensing the change in rolling radius of a tyre as it deflates has been proposed (**6**). The signals for this approach are taken from the advanced braking system (ABS) thereby limiting its application to vehicles with ABS, otherwise it will be necessary to fit suitable sensors with additional cost implications.

An alternative system is proposed in this paper which relies on measuring the vibration of the wheel/axle subsystem as the vehicle is driven in the normal fashion. Subsequent analysis of the vibration should enable

(a) the tyre stiffness to be determined and this can be related to inflation pressure;
(b) quantitative determination of the damping in the system and hence damper condition; and
(c) estimation of the degree of wheel out of balance.

2 THEORY

The quarter car model is widely used for simplified dynamic analysis of vehicle vibration. The two degree-of-freedom system shown in Fig. 1 results in the following equations of motion:

$$m_s \frac{d^2 x_s}{dt^2} + k_s(x_{us} - x_s) + c\left(\frac{dx_{us}}{dt} - \frac{dx_s}{dt}\right) = 0 \qquad (1)$$

$$m_{us} \frac{d^2 x_{us}}{dt^2} + k_s(x_s - x_{us}) + c\left(\frac{dx_s}{dt} - \frac{dx_{us}}{dt}\right) + k_t x_{us} = k_t x_g \qquad (2)$$

As a first approximation damping can be neglected and if $x_g = 0$, then harmonic motion can be assumed

$$x_s = X_s \sin(\omega t) \qquad \text{and} \qquad x_{us} = X_{us} \sin(\omega t) \qquad (3)$$

The characteristic equation is obtained

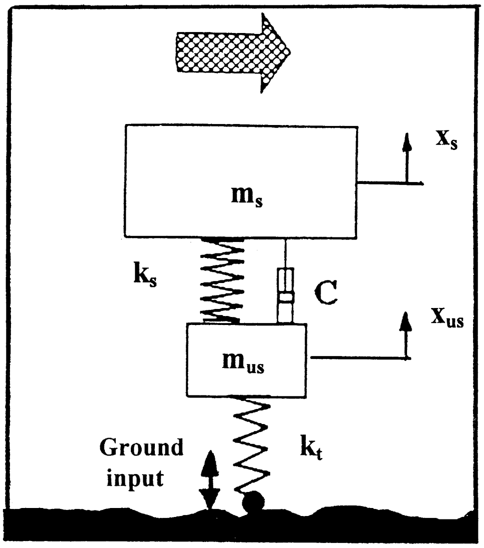

Fig. 1 The quarter car model

$$\omega^4 - \omega^2 \left[\frac{k_s}{m_s} + \frac{(k_t + k_s)}{m_{us}}\right] + \frac{k_s k_t}{m_s m_{us}} = 0 \tag{4}$$

The solution of this quadratic yields the two natural frequencies for the system

$$2\omega^2 = \frac{k_s}{m_s} + \frac{(k_t + k_s)}{m_{us}} \pm \sqrt{\left\{\left[\frac{k_s}{m_s} + \frac{(k_t + k_s)}{m_{us}}\right]^2 - \frac{4k_t k_s}{m_s m_{us}}\right\}} \tag{5}$$

Taking typical parameter values as $k_t = 180\,000$ N/m, $k_s = 22\,000$ N/m, $m_{us} = 30$ kg, $m_s = 450$ kg results in $\omega_1 = 6.59$ rad/s and $\omega_2 = 82.3$ rad/s (i.e. $f_1 = 1.05$ Hz and $f_2 = 13.1$ Hz).

If the tyre is underinflated then the vertical stiffness k_t is likely to be reduced. This will affect the natural frequencies of the system especially f_2. As an example, if k_t reduces by 50 per cent then, from equation (5), f_2 decreases by 25 per cent. Detection of this change in f_2 is the basis of the proposed tyre pressure monitoring system. Variation in the values of the sprung mass m_s and the suspension stiffness had little influence on f_2 as shown in Table 1.

3 STATIC TESTS

To determine the typical reductions in k_t, two makes of tyre were loaded statically in a materials testing press. Measurements of load and deflection were recorded for various tyre pressures. The tyres were from the test vehicle which was available and were partly worn with approximately 3 mm of tread remaining. Details are given in Table 2.

Figure 2 shows the results of the static tests. The weight of the test vehicle was taken from the manufacturer's data and resulted in a steady design load on the tyre of 3.65 kN (820 lbsf). The slopes of the curves shown in Fig. 2 were determined graphically at this design load to obtain linearized stiffness values. These values of k_t are plotted for the two tyres in Fig. 3. Tyre 1 showed a reduction in stiffness of 43 per cent when the pressure was reduced from the design value of 1.79 bar (26 psi) to 0.96 bar (14 psi). Tyre 2 showed a reduction of 28 per cent in stiffness for the same pressure drop.

Table 1 Influence of system parameters on f_2 [from equation (5)]

m_{us} (kg)	m_s (kg)	k_t (N/m)	k_s (N/m)	f_1 (Hz)	f_2 (Hz)	Comment
30	450	180 000	22 000	1.05	13.1	Datum
30	675	180 000	22 000	0.86	13.1	50% increase in m_s
30	225	180 000	22 000	1.48	13.1	50% reduction in m_s
30	450	180 000	33 000	1.25	13.4	50% increase in k_s
30	450	180 000	11 000	0.76	12.7	50% reduction in k_s

Table 2 Volkswagen (VW) Passat tyres used for static tests

Tyre number	Make	Size	Tread plies	Sidewall plies
1	Michelin MX	165 R 13 82S	1 Rayon, 2 Steel	1 Rayon
2	Silverstone Firefox	185/70R 13 86H	1 Polyester, 2 Steel, 2 Nylon	2 Polyester

4 DYNAMIC TESTS

4.1 Tyre pressure

A Monitran MTN/1800 (**7**) accelerometer was mounted at the base of the suspension strut on the front nearside wheel of a VW Passat running on tyre type 2 (Fig. 4). A test route on public roads was identified which was approximately 12 km in length incorporating both rural and urban roads. The tyre pressure was set using a Budenburg pressure gauge (range 0–3.4 bar (0–50 psi), least count 0.034 bar (0.5 psi)) to the required value in the range 1.24–2.07 bar (18–30 psi). The car was driven around the test route in a normal fashion and the vibration recorded on a TEAC DAT tape recorder. An average speed of 48 km/h (30 mile/h) was attained for most tests. On completion of the tests, the data were played back through an Ono Sokki 920 analyser and a personal computer (PC).

Approximately 15 min of data were acquired from each test run and these were used to obtain an averaged spectrum over the frequency range 0–20 Hz. Figure 5 shows the spectra obtained for tyre pressures of 1.24, 1.79 and 2.07 bar (18, 26 and 30 psi). The data from the spectra were fed into a PC and the curves smoothed in the region of the second natural frequency f_2. It was found to be necessary to include 61 spectral estimates (a bandwidth of 3 Hz) to achieve a smooth spectrum from which a reliable peak value could be identified and the corresponding frequency ascertained. Figure 6 shows the smoothed spectrum for the 1.79 bar (26 psi) test data.

The smoothed spectra were used to identify the value of f_2 for each tyre pressure and these were then plotted to form the calibration curve (Fig. 7) for the monitoring system. A straight line was fitted to the data using the least-squares approach which resulted in the relationship

$$p = -4.56 + 0.487 f_2 \tag{6}$$

To evaluate the accuracy of the proposed approach to measuring tyre pressures the tyre pressure was then set at an unknown value within the test range and the test run was repeated. The data were analysed as previously and the measured frequency was used to predict the tyre pressure [based on equation (6)]. The actual tyre pressure was measured after the test run using the Budenburg pressure gauge. This procedure was repeated for a second unknown pressure setting and the results are shown in Table 3.

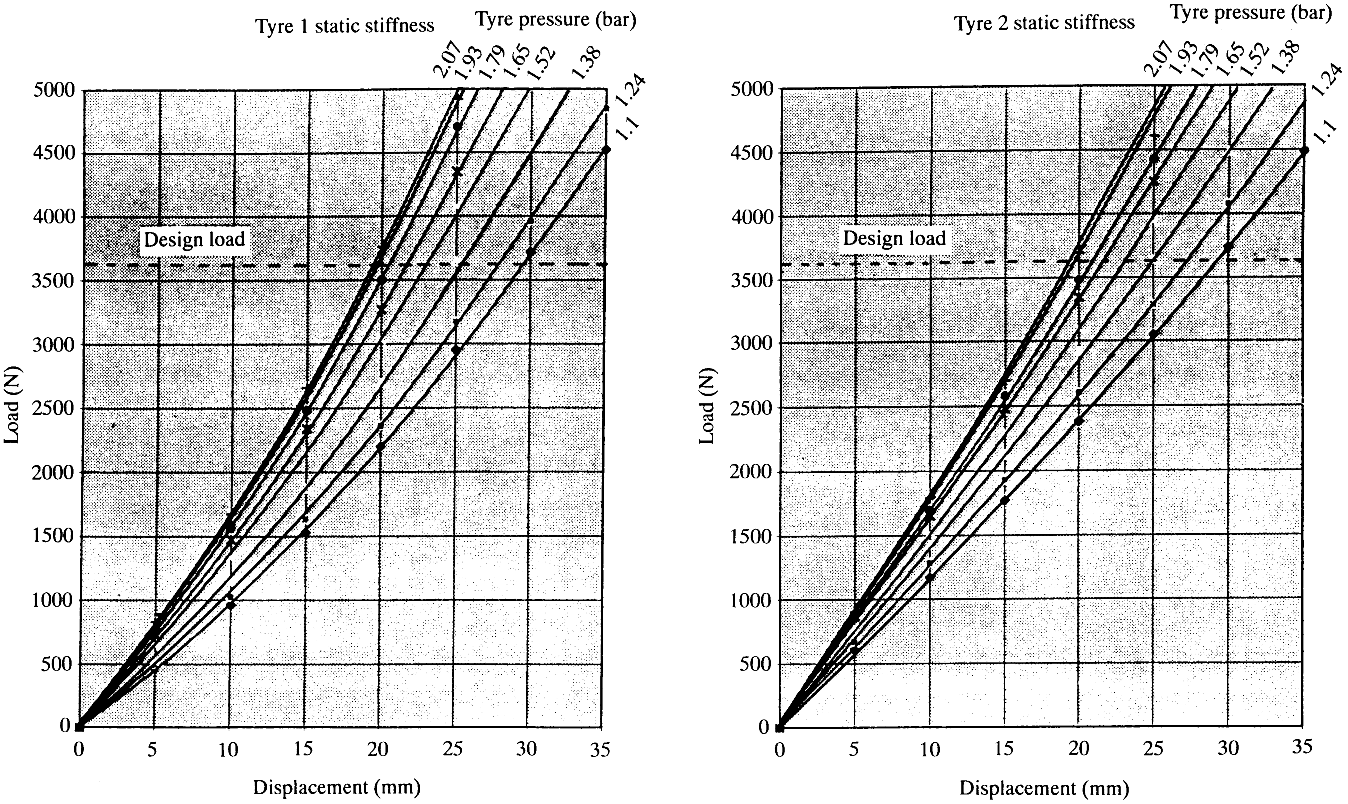

Fig. 2 Static force–deflection curves for the two types of tyre

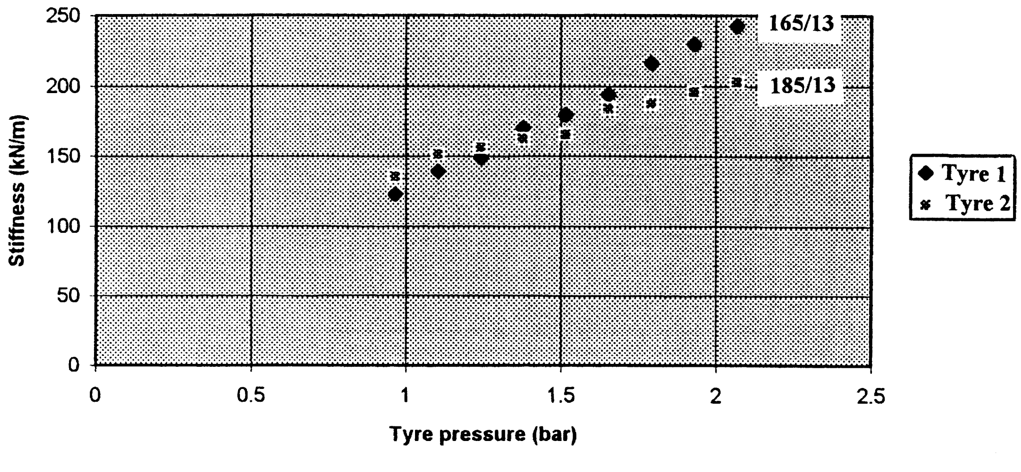

Fig. 3 Linearized static stiffness for the tyres as a function of tyre pressure

4.2 Damping

If the spectrum of the wheel/axle vibration is measured, it is possible to obtain an estimate of the damping in the system by determining the Q factor. The value of Q is given by determining the bandwidth of the peak associated with the natural frequency f_2 at the half power points and dividing this into the value of the natural frequency. For the tests carried out this resulted in values of $Q = 1.7 \pm 0.2$ (Figure 8 shows the evaluation of Q factor for the 1.79 bar (26 psi) test.) An estimate of the damping factor ζ can then be obtained

$$\zeta \approx \frac{1}{2Q} = 0.29 \qquad (7)$$

Fig. 4 Photograph of an accelerometer mounted on a suspension strut

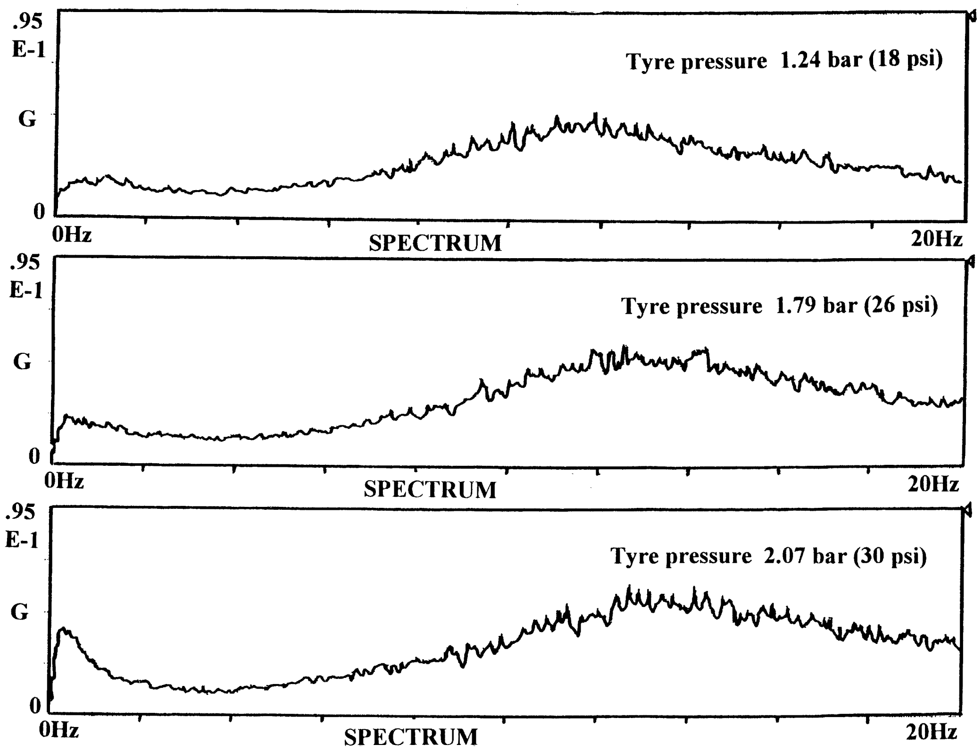

Fig. 5 Some of the averaged spectra recorded

although this approximation is only strictly true for lightly damped systems.

As the damper becomes worn it is to be expected that the peak at f_2 will become sharper and the Q value will rise. A 'warning' level could be identified from further testing to indicate when damper replacement is necessary.

4.3 Wheel balance

If a wheel exhibits out of balance then vibration transmitted through the steering wheel and vehicle body can be a problem. Such vibration is detrimental not only to driver comfort but increases tyre wear and steering linkage/joint wear. A transducer mounted on the wheel/axle would be

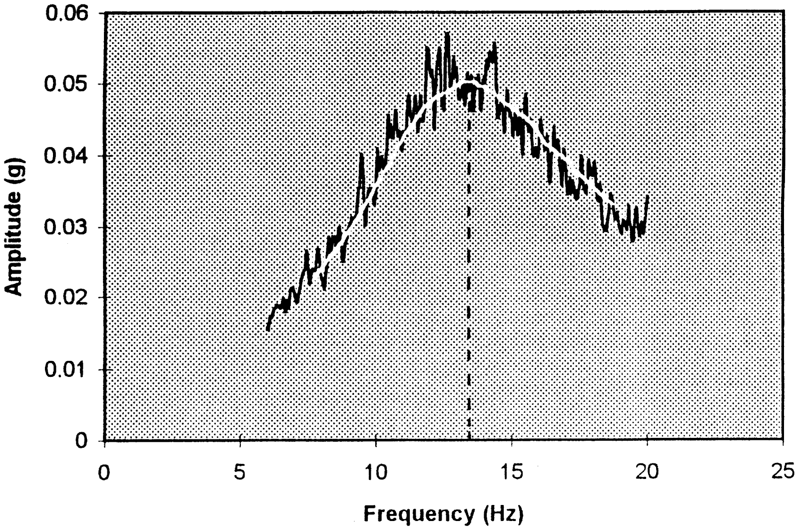

Fig. 6 The smoothed spectrum for the 1.79 bar data

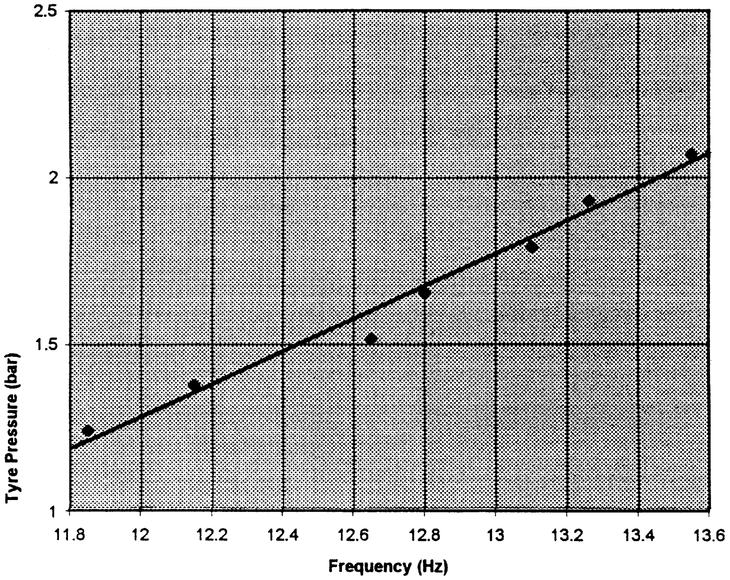

Fig. 7 The calibration curve for tyre 2

Table 3 Pressure monitoring system test results

	Pressure predicted		Pressure (gauge)		% Error
	(bar)	(psi)	(bar)	(psi)	
Test 1	1.57	22.8	1.586	23	−1
Test 2	1.16	16.8	1.31	19	−11.6

able to detect vibration at lower levels than the average driver and provide a warning when wheels should be balanced. Increases in wheel out of balance will result in higher levels of vibration at the fundamental wheel rotational frequency and its harmonics. Measurement of the vehicle speed coupled with a knowledge of the tyre effective radius will enable the fundamental frequency at that point in time to be determined. Filtering techniques could then be used to estimate the level of wheel unbalance and whether remedial action is necessary. Figure 9 shows the results of tests carried out at a steady speed of 100 km/h and clearly shows the fundamental frequency and its harmonics. This was for a well-balanced wheel on a motorway so it should be possible to detect increases in these levels. The wheel radius was 0.32 m so at 100 km/h the fundamental frequency is

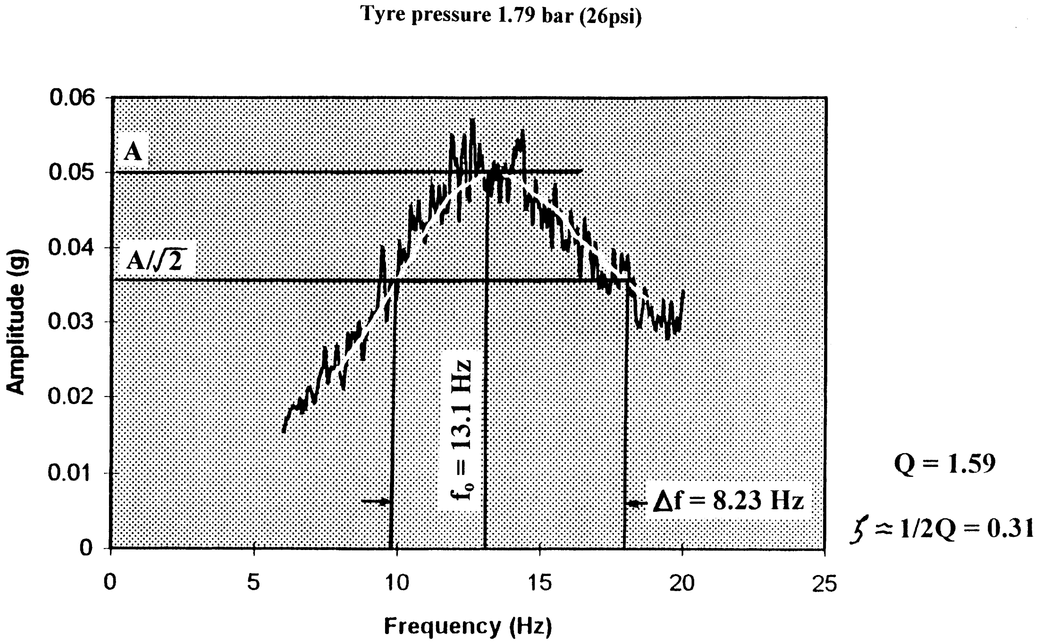

Fig. 8 Determination of the *Q* factor

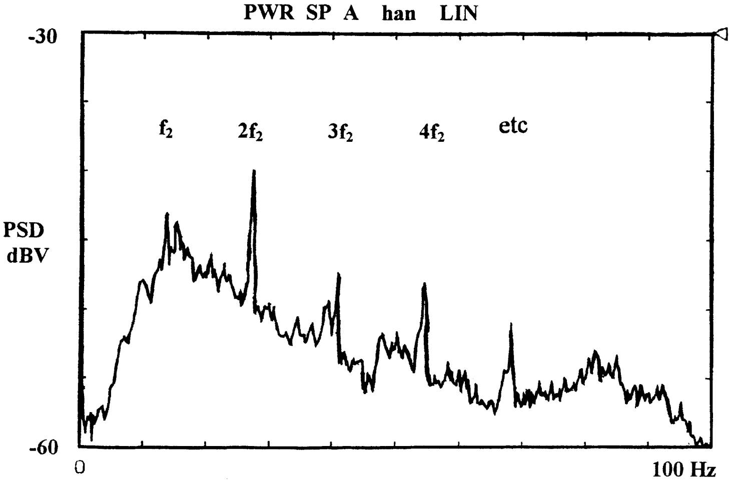

Fig. 9 Averaged power spectral density at a constant speed of 100 km/h

$$f = \frac{v}{2\Pi r} = \frac{27.77}{2\,\Pi\,0.32} = 13.8\ \text{Hz} \tag{8}$$

5 DISCUSSION

The work presented describes the initial development of a wheel station monitoring system. There is little doubt that information regarding tyre pressures, damper condition and wheel balance would be of benefit to the motorist in terms of safety and economy. However, care will have to be taken not to overload drivers with information when things are satisfactory and it will be important to avoid 'false alarms'.

The proposed system (Fig. 10) will involve four transducers (for a four-wheeled vehicle). Accelerometers would be the obvious choice but velocity of displacement transducers could be used if they were more economical. An analogue-to-digital (A/D) converter, microprocessor and display unit would also be required. The performance of the A/D converter and processor would not need to be great because a sampling rate per wheel of 50 samples/s would be sufficient to produce a spectrum over the range 0–20 Hz. Therefore, for a four-wheeled vehicle the processor would be required to handle 200 samples/s. The transducers are likely to be the most expensive components within the system but widespread current research efforts (**9**, **10**) show promise of cheaper accelerometers in the near future. Also, many cars with advanced suspension systems

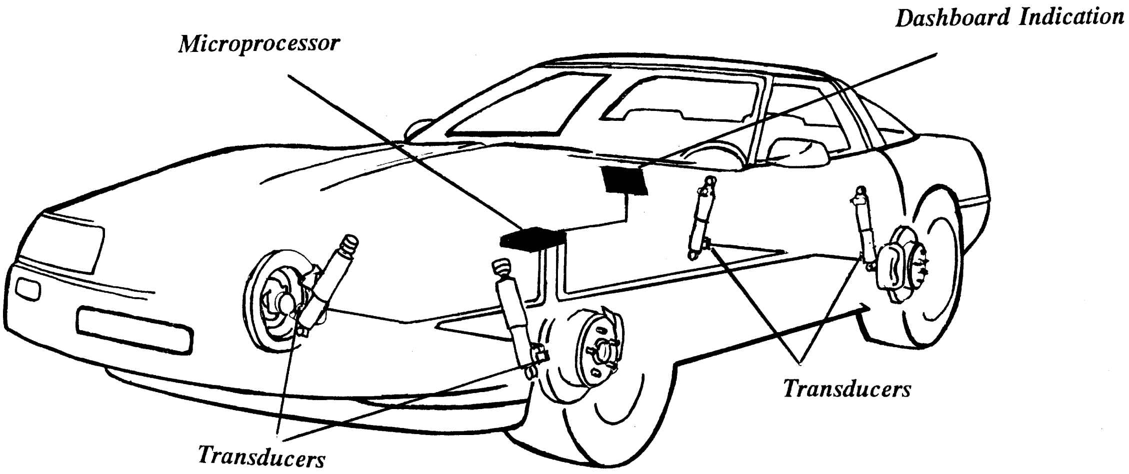

Fig. 10 The proposed system

are likely to employ suitable transducers already, so in these vehicles the signal could be obtained at virtually no extra cost. It is thought that the proposed system could be produced at a price which would be attractive to all sections of the market.

The tyre pressure measuring system was shown to be accurate to within 12 per cent for one test and to within 1 per cent for a second. An average accuracy of ±5 per cent is considered possible with continuous averaging and smoothing. The tests reported were based on tyre type 2 which showed the smaller change in stiffness for a given change in pressure. Tests with the more 'sensitive' tyre are likely to result in better accuracy.

It would be necessary to employ exponential averaging for the system to respond to changes in pressure that would occur with a puncture. From Fig. 3 it can be seen that the approach is dependent on the make of tyre fitted to the vehicle so an integral calibration facility would be required if different tyres were fitted to the vehicle. Changes in the other parameters of the system, e.g. sprung mass and suspension stiffness, were found to have very little influence on f_2 and hence the accuracy of the approach. One of the main benefits of this approach for finding tyre pressure is that, unlike many of the other systems developed so far, this one does not involve an additional breach of the tyre air space thereby eliminating any increased chance of leaks and deflation.

The indication of damper condition is readily obtained from the spectrum and consistent results were obtained for the case tested in the present study. However, further research is needed to determine values of Q which would indicate that dampers should be replaced. This approach to determine damper condition would also seem to be appropriate for regulatory bodies involved in vehicle testing (such as the MOT test in the United Kingdom).

The possibility of an indication of wheel unbalance can be seen from Fig. 9. However, a considerable amount of signal processing will be required to obtain an accurate assessment. The fundamental frequency and harmonics are not only due to unbalance but also circumferential variations in tyre stiffness and dimensions. However, it is considered that when a wheel requires balancing this effect will dominate these frequency components of the signal. It will be necessary to develop a digital bandpass filter which can track the fundamental frequency and probably the first harmonic. The unbalance force varies with velocity squared and the non-linear response of the system will add to the complexity. However, it is considered that these problems could be accounted for in the software.

It is considered that the initial work reported shows that it would be feasible to produce an inexpensive system that could provide drivers with an indication of tyre pressures, damper condition and wheel balance to improve safety, comfort and economy in modern vehicles.

6 CONCLUSIONS

A wheel station monitoring system has been described based on sensing the vertical vibration of each wheel/axle subsystem. Initial results have shown that tyre pressures were measured to an accuracy of 12 per cent and that damping and degree of wheel unbalance can be determined. Further work is required to improve the accuracy and reliability of the system and so provide an on-board indication of these parameters for drivers, to increase safety, ride comfort and economy.

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