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# Interferometric rail roughness measurement at train operational speed

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**Abstract**

Measuring rail roughness in view of reducing rolling noise emission is a challenge for field instrumentation. Direct measurements can be carried out with contacting relative displacement measuring systems. However, the rail length that can be covered is limited and surveying a wide network turns out not to be practical. On the other hand, indirect methods based on acceleration measurements may be used for monitoring purposes. In this paper, the feasibility of roughness measurements based on interferometric techniques is discussed. Such a measurement could be carried out at normal train operation speed. The problems of optical measurements in real-time conditions are taken in due consideration. A key point of the discussion is the use of a system for vibration attenuation to be mounted under a vehicle to suspend the optical sensing device. The structure for a complete measurement device is proposed together with the expected performance.


## 1. Introduction

New European rules for trains will be adopted in determining noise emission levels. In particular, some European technical specifications will be introduced for new interoperable high-speed trains. New rules for conventional interoperable passenger trains and freight trains will soon follow [1–6].

Train noise is mainly related, for normal operating speeds, to rail and wheel roughness [7]. Roughness on a rail is the vertical rail displacement difference between the ideal rail surface and the real one. This defect, of the order of some microns, is characterised by a broad-band wavelength spectrum. On the wheel, roughness is measured as the difference between the ideal wheel circumference and the real one. Here a broad-band wavelength spectrum is also present, but peaks could be found typically for 4–10 cm wavelength, depending on the braking system of the train.

Rail and wheel roughness excite vibrations of wheel, bogie, rail, sleeper and ballast [8]. The effect of roughness of rail or wheel is felt in the same way, since a relative displacement with respect to ideal position is introduced in between. In other words, if one of the two roughness levels is dominant, this will cause all

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sources to increase, and not only those on the side of roughness (e.g.: if wheel roughness is dominant, rail, sleeper and ballast contribution will be high, too). Due to this, train noise may vary between a test track site (with low or very low roughness level) and a normal operating condition track (sometimes highly corrugated). In the latter case, rail roughness may be much larger, generating a larger track and vehicle vibration resulting in a higher noise.

Studies about roughness influence have been done in the past [9] and are still matter of research at the present. This knowledge allowed to write the Pr EN ISO 3095 [10], which is still a draft. In Pr EN ISO 3095, the roughness spectrum of a test track is required not to exceed a certain level. This will allow comparisons of noise from trains measured on several test tracks in Europe [11], and ensure that noise at another site could be estimated.

In the standard, the measuring instrument specifications are not stated. Only a range of the instrument is given, which is between −20 and +30 dB re 1 μm and the requirement of parallel line measurements for a wide rolling band is stated. Nothing is further specified about the measurement technique, which may also have a certain influence.

Because of lack of knowledge, in recent times trains were mostly classified on the basis of noise measurements only, using several sites and several trains and assuming that a typical condition can be determined, which may exist at any place. If roughness will be measured through potential new measurement instruments, more accuracy will be achieved and there will be less need to tune prediction models.

In recent years several roughness measurement instruments were developed [12,13], which allowed roughness spectra to be characterised [14]. Systems were mainly developed to get rail roughness spectra, but a few wheel roughness measurement instruments were also made. RM1200E [15] is the most known rail roughness measurement device which uses a linear displacement transducer with a contact tip on the rail surface with a resolution of about 0.01 μm. The Corrugation Analysis Trolley [16–18] uses an accelerometer in contact with the rail. By double integration of the signal, a resolution of the order of 0.01 μm is achieved in that case too. The RM1435 is an instrument to measure train wheel roughness based on the same principle as RM1200E using two linear displacement transducers touching the wheel radially to allow the measurement of both wheels synchronously and a small wheel to trigger the measurements equidistant on the train wheel circumference.

During 1999, in Utrecht, a comparison [19,20] between different measurement systems was done and other methods were also presented, like axlebox accelerometer systems [21,22] and wagons with mounted microphones [23].

Train and track roughness may also be derived via indirect measurements (e.g. using vertical rail vibration and PBA software, produced by TNO [24]), once at least one of the two roughness spectra is known.

Direct roughness measurements are obviously time consuming and expensive and can be performed only on limited portions of the railway network, namely test track sites. On the other hand, several indirect measurements could be used systematically over the network and allow statistical observation of train noise, and overall could be used to monitor wear and allow planning of maintenance in a more effective way. These indirect methods however rely on the effect of roughness on wagon dynamics and noise that may be quite complicated to model. The situation of roughness measurement appears in many aspects unsatisfactory: while knowledge on the subject has progressed significantly [25,26], further investigation requires dedicated effort. Worse is the fact that benefits from roughness reduction through planned rail acoustic grinding can be elusive, by lack of monitoring tools and not by lack of maintenance means.

This work addresses the hypothesis of designing a non-contacting roughness measurement device that can possibly operate at normal train speed. The measurement is based on interferometry using visible light, although it is more appropriate to speak of "Holographic Interferometry" [27] as the rail is an object rather than an optical component. The position measurement is an average over a light spot typically of size 1–2 mm that may be modified using an appropriate optical setup. Optical distance measurement must be done from an appropriate reference system, moving on a straight line. This work proposes to use an inertial platform as reference system to support the optics. The system has to be integrated with up-to-date read-out peripherals and data processing tools. In the following, the measurement system is discussed together with future developments.

## 2. Principle of operation

### 2.1. Interferometry

Optical distance measurements can achieve excellent resolution when interferometric techniques are used. Indeed, simply counting dark and bright interference fringes, their spacing being determined by the wavelength of light, ensures submicron precision. This can be taken to the extreme by searching a minimum of the dark fringe of the interference pattern. In that case, the measurement is mostly plagued by light intensity fluctuations (or more appropriately statistical fluctuations in counting light quanta) and variations of the light source wavelength. As an example where this technique is stretched to the limit is the position measurement achieved in fundamental science: gravitational wave interferometric detectors [28–31], designed to test Einstein's General Relativity, have a noise floor of $10^{-18}$ m integrated over a bandwidth of 1 kHz.

Without pushing technology that far, a noise floor of −20 dB re 1 μm can be achieved nowadays using red light lasers similar to the pointing devices used in oral presentations. Indeed the phase variation of light making a round trip between two points separated by $L$ is

$$\Delta\phi = 2\pi 2L/\lambda, \tag{1}$$

where $\lambda$ is typically 0.64 μm. When the reflected light interferes with a reference light beam, the intensity will depend on $\Delta\phi$. Two successive minima of intensity are met when distance varies by 0.32 μm. By interpolating between maxima and minima, 0.1 μm resolution can easily be achieved.

At this level of precision, fluctuations in laser wavelength are not important. However, the light source must have a coherence length larger than $2L$ to preserve the phase relationship between reflected and reference beam. These requirements are easily met in an application with $L$ of the order of 0.1 m.

### 2.2. Inertial damping

The idea of having a non-contacting measurement is in contrast with the need for a reference line to compare roughness to. It is proposed here to use an inertial platform to obtain a reference system with low position noise so that it can be considered moving on a straight line. This inertial platform should support the optical system for distance measurement and be suspended from the bogie of a coach. It is well known that a mechanical oscillator can provide vibration isolation at frequencies higher than its resonance frequency. For an oscillator with mass $m$ and elastic constant $k$, the transfer function from the position of the end of the spring to the mass position is given by

$$|H(\omega)| = \frac{\omega_0^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + \omega^2\omega_0^2/Q^2}}, \tag{2}$$

where $\omega_0 = \sqrt{k/m}$ is the undamped resonance frequency and $Q$ is the quality factor. For $\omega^2 \gg \omega_0^2$, the transfer function becomes

$$|H(\omega)| = \frac{\omega_0^2}{\omega^2}. \tag{3}$$

This property can be used to provide the necessary reference system by limiting measurements to sufficiently high frequency. Again this is applied in gravitational wave detectors in order to isolate the mirrors that act as test masses from local disturbances. The requirement on local vibration attenuation must be better than interferometer precision in the frequency band of measurement. This has been achieved at frequencies as low as a few Hz [32]. As will be seen below, the specifications for roughness measurement allow to use this comfortably.

There is, however, a serious inconvenience: to achieve this attenuation, the oscillator cannot be strongly damped and oscillation at the resonance frequency may be of high amplitude. This may cause too high a motion in a frequency range uninteresting for the roughness measurement but this may drive the system too far away from its working point. To avoid this inconvenience, the mass motion must be actively damped in a selective way as a function of frequency. Such an "inertial damping" is also used in interferometric gravitational wave detectors to keep the optical resonant cavity at its maximum sensitivity [33]. With the use of accelerometers measuring the mass motion and acting on the mass itself, it is possible to achieve an acceptable oscillation amplitude.

### 2.3. Principle design of a non-contacting roughness measurement device

The proposal consists in having an inertial platform suspended from the bogie of a coach to provide a reference system moving on a straight line over an interval of time not more than $10^{-2}$ s. This platform will support the optical system for the roughness measurement. The electric signal collected by the camera can then be taken by cable to analogue and digital processing units that will provide the measurement. A full instrument should then be interfaced to other devices such as a TV camera and a GPS receiver for systematic measurement localisation and to a microphone and an accelerometer for the necessary cross checks of measurement. A principle sketch of the main measurement part is shown in Fig. 1. Where parallel track measurements are required, a simple solution would be to duplicate the optical part on the same inertial platform.

Developing the instrument in the laboratory first will allow the best suited and most robust configuration to be determined for field operation. In spite of the complexity of the task, the components needed for a prototype are common and can be procured without difficulty. This makes the authors confident that a feasibility study can be done rapidly.

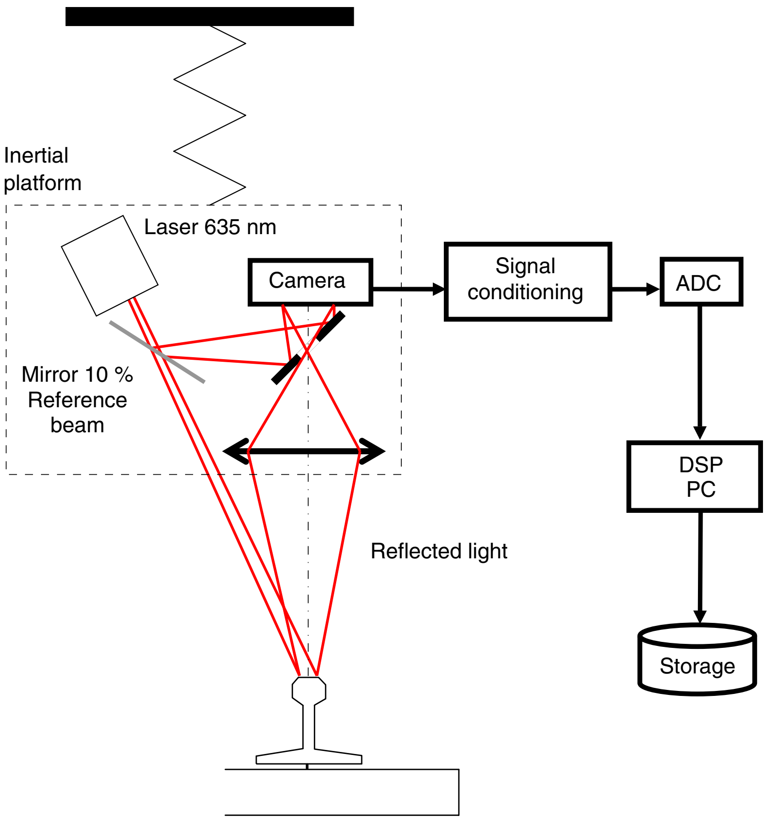


Fig. 1. Principle configuration for roughness measurement. The laser, optical components and camera must reside on the inertial platform, which should be rigid enough to preserve optical paths.

## 3. Performance evaluation

### 3.1. Inertial platform noise

The bench that supports the optical components must behave as a passive vibration filter in the measurement frequency band and its motion should be actively damped to avoid too large an excitation of the normal modes. Vibration isolation has to occur in all six degrees of freedom, as optical measurements are quite sensitive to angular fluctuations.

To illustrate the requirement on the inertial bench, the proposed ISO 3095 limit has been used. The curve, which specifies roughness in one-third octave band, has been translated in an equivalent Linear Power Spectrum, expressed in $\mu m/Hz^{1/2}$. This spectrum has been used as excitation of the upper end of the inertial platform suspension spring. The resulting position noise has then been obtained using the transfer function equation (2) with $Q = 10$. Wheel resonances and bogie suspension are neglected: bogie suspension shall provide a further mechanical filter, reducing additionally the position noise; wheel resonances occur at high frequency where vibration attenuation is fully efficient. The resulting position noise spectrum is plotted in Fig. 2, assuming a 1/10th fringe resolution.

### 3.2. Precision of distance measurement

The intrinsic precision that can be achieved with interferometry is determined by the light wavelength and the number of detected light quanta $N_\gamma$:

$$\sigma_x \approx \frac{1}{2\pi} \frac{\lambda_{\text{light}}}{\sqrt{N_\gamma}}, \tag{4}$$

$N_\gamma$ is usually respectable but will decrease according to the measurement sampling rate. Indeed the results shown in Fig. 4 could be achieved with a 10 mW source of light.

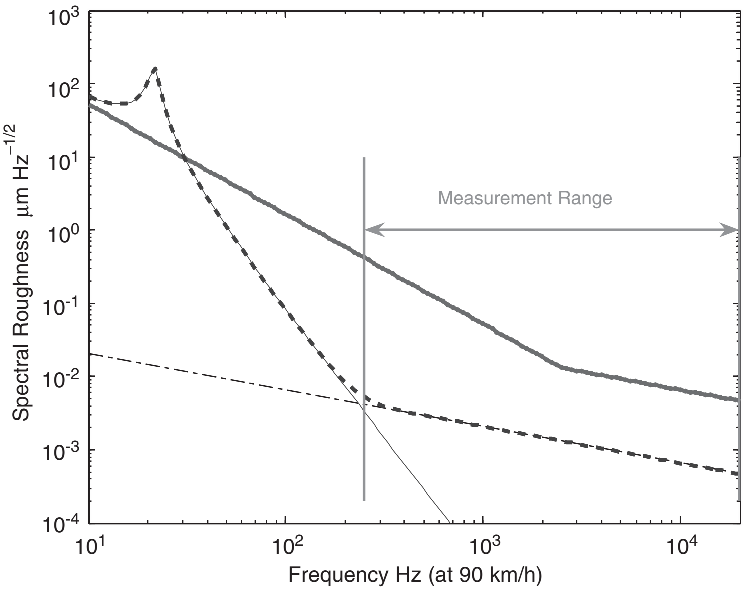


Fig. 2. Contribution to the noise in roughness measurement. Thin line: platform noise; dot dashed line: 1/10th fringe spacing; dotted line: total noise; solid line: pr EN ISO 3095 limit. Note that the plot refers to roughness Linear Power Spectrum, which is the rms integrated over a 1 Hz frequency band. This is why the ISO 3095 limit curve is tilted. One sees that already at 100 Hz position noise is very low with respect to the limit curve. The line referring to 1/10th fringe spacing is obtained assuming that for every 1/3rd octave band a precision equal to 1/10th fringe spacing ($\lambda_{\text{light}}/20$) can be achieved.

Other less fundamental causes can spoil the measurement precision. An insufficient control of the geometry and alignment of the measurement device with respect to the rail may change the interference pattern in a way similar to displacement: however, the required angular precision for the light beam direction is estimated to be of the order of 100 μrad for an alignment accuracy of 10 mrad (1 mm over 0.1 m). This appears to be compatible with the expected performance of the inertial platform. The dynamic range allowed by the camera can also be a limit: laser light scattered back from a rough surface shows high-intensity speckles that may saturate the analogue-to-digital converter or worse the solid-state camera itself. If not dealt with properly, this may cause short interruptions in the measurement. It is expected that read-out devices capable of measuring light intensity over a relative range of 1000 will be sufficient. In view of these uncertainties a specific research proposal has been funded, with the main goal of establishing the optical measurement performance and studying the inertial platform stability requirements in all 6 degrees of freedom.

### *3.3. Read-out issues*

Operation at usual train speed sets a stringent requirement for the performance of the read-out system. Acquisition of the interference pattern must occur at the highest foreseen frequency that will be taken here as 20 kHz. In the demonstration test, the initial fringe pattern was recorded as an image. However, the volume of data used to analyse displacement was 256 bytes, using intensity representation based on the scale 0–255 (1 byte).

These data can be used to estimate the requirements on the read-out and storage system. Sampling at 40 kHz would produce a data flow of 10 Mbyte/s. It would be appropriate to reduce the data during operation to record only the distance measurement (2 bytes), storing 80 kbyte/s on disk. Nevertheless, part of the system must be able to sustain a 10 Mbyte/s data flow. On the other hand, availability of faster digital components will allow in the future to increase sampling rate to take data at higher speed or at lower roughness wavelength. In this case, a 1 h trip would produce about 300 Mbyte of data while recording a 256 byte fringe profile would result in 36 Gbyte and a hypothetical complete movie would result in 44 Tbyte. In perspective, even the last figure may not be impossible to achieve, if necessary.

## 4. Data analysis

### *4.1. Fringe analysis from a laboratory test*

In order to assess the techniques potential an holographic interferometry setup was assembled consisting of a 10 mW He–Ne laser and medium-quality optical components. The head of a rail segment was illuminated and the optical path of the incident beam was varied by means of a mirror glued on a piezoelectric crystal. A signal of known shape was applied to the crystal to obtain a motion amplitude of the order of 1 μm. Pictures were recorded using a commercial low-cost web cam connected to a PC. Data were stored on disk and analysed offline using the basic functions of the MATLAB [34] scientific programme.

To use a simple model for the fringe pattern an area with straight interference fringes was selected, as shown in Fig. 3. Intensities were then summed column-wise resulting in a 256-component vector. Then a Fast Fourier Transform was applied and the maximum frequency component in modulus was identified for the full dataset. Position was deduced from the phase of that component. Phase discontinuities were identified to produce a smooth measurement. For technical reasons, only one frame out of three was accessible. The result is shown in Fig. 4 for a sawtooth signal applied to the piezoelectric crystal.

### *4.2. Fringe analysis in the foreseen apparatus*

The requirement for a fast real-time analysis leads to investigate several points. All elements of the read-out chain are critical in order to achieve a 40 kHz read-out rate. Starting upstream, it is proposed to use a line scan camera with analogue output in order to preserve a large dynamic range, that is the ratio of the signals of maximum light intensity and of no light at all. Current basic models [35] allow reading a 1024 pixel line at 40 MHz with dynamic range around 2500. Digital 8-bit output is also available at the same read-out rate.

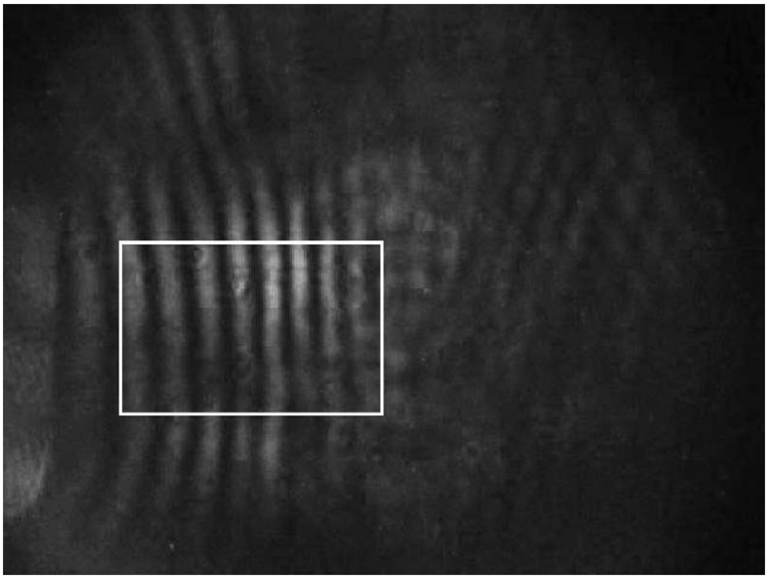

Fig. 3. Typical interference pattern from the rail surface illuminated by a Helium Neon laser beam and compared to a reference beam. The optical path is varied at slow speed by means of a piezoelectric actuator and the fringe pattern is recorded as a function of time. The white rectangle identifies the region of interest for data analysis.

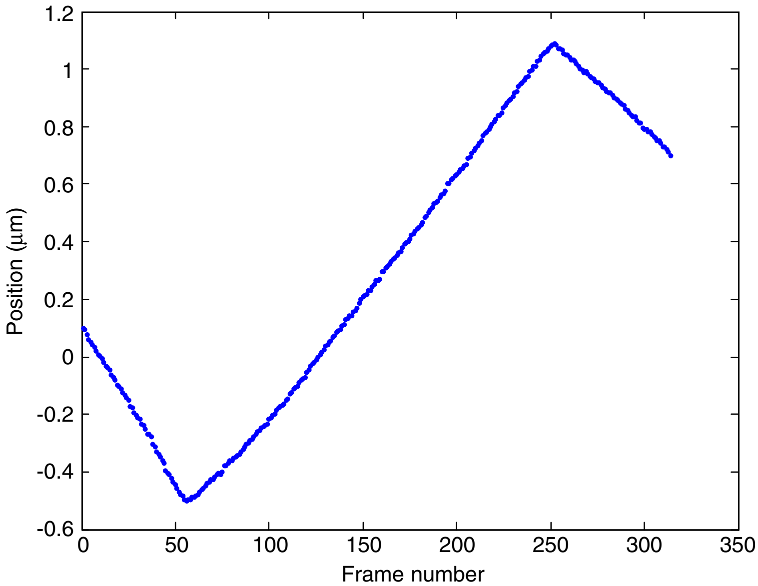


Fig. 4. Result of the analysis of fringe motion recorded by a low-cost camera at 25 frames per second. One frame out of three is analysed, resulting in steps on the graph. A resolution better than −20 dB re 1 μm is reached. The small nonlinearity is most likely due to the approximate optical model used for position reconstruction.

Analogue to digital conversion can then occur with 12-bit dynamics. If the fringe pattern turns out to be essentially periodic, one could envisage to have a phase-locked loop to follow fringe displacement in an analogue way. Otherwise, digital signal processing allows the position parameter to be extracted from the fringes. In principle, on-line statistical analysis of fringes could provide directly a roughness spectrum but again this has to be investigated in real conditions.

### 4.3. Statistical analysis

The perspective of having large samples of roughness measurements together with sound recording and precise position information can trigger a systematic diagnostic of a railway network. In particular, by using the same train for all measuring campaigns the relative contribution of several different rail roughness conditions can be compared systematically. Reproducibility of the measurements of sound pressure, acceleration and roughness could be verified with a single train, providing better reliability to the whole procedure leading to railway noise reduction.

## 5. Conclusions

The measurement of rail roughness using interferometry looks promising. The requirements for operation at normal train speed are met for a measurement performed under laboratory conditions. A significant amount of work needs to be done to fully master the unavoidable complexity of field work. However, the instruments needed seem to be there, as well as theoretical understanding and this makes the authors confident that progress in this matter will occur.

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