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Velocity and Location Information from Onboard Vibration Measurements of Rail Vehicles

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***Abstract*—Vehicles in motion are exposed to mechanical vibrations, resulting from various sources, such as the engine, transmission, wheels, the track and many more. Vibrations in vehicles are often undesired, but these vibrations contain navigation and vehicle information. In addition to state-of-the-art techniques for the computation of spatial vehicle movements from inertial measurements, the vibration measurements can also be used explicitly for navigation with appropriate methodologies. This first study focuses on vibrations in a diesel engined passenger train, measured by a vertical, translative acceleration sensor. The major vibration sources of a train in motion are identified in an analysis and characterized by speed dependency or independency. We present procedures to separate and filter these vibrations in combination with a simple model of the vehicle. This paper presents new methods to infer vehicle speed and the wheel diameter measurements for a wheel diagnostic monitoring during motion. Furthermore a rail vehicle localization is achieved based exclusively on vibrations measured by one accelerometer and a correlation technique. We show promising track-selective train localization results by the location dependent vibrations, discuss improvements and an integration in a multi sensor localization approach as well as the advantages and drawbacks of vibration based navigation.**

I. INTRODUCTION

Vehicle vibrations are oscillatory motion caused by many different sources and the vehicle response, which result mostly in complex vibrations of multiple frequencies, magnitudes, and orientations. Vibrations can be categorized in stationary or non-stationary, or random versus deterministic. Deterministic vibration includes periodic motion or transient and shock [1].

Vibrations in vehicles are mostly unwanted for passengers comfort or lifetime of mechanic structures, joints and electric hardware. In terms of passenger comfort [2], vibrations can cause discomfort, in which low frequency vibrations affects vestibular system and haptic perception, and higher vibration frequencies emit as well acoustic noise. In general, vehicle design concentrates on the reduction of vibration, also known as NVH engineering (noise, vibration, harshness). In inertial navigation, vibration is not desired as well and often suppressed and canceled by filter techniques [3].

Vehicle vibrations can also be desired in some cases, as they provide feedback of vehicle motion to the driver or for engine or gearbox diagnostics [1]. There are only few vibration approaches for navigation, such as [4], in which an underwater localization system is proposed based on vibration measurements with a sensor array similar to the lateral line system of a fish. A terrain classifier of a vehicle in [5] differs between sand, gravel, or clay based on vibration measurements during motion. A speed computation from accelerometer measurements of a vehicle driving over street bumpers was presented in [6].

In a previous work, we analyzed the inertial effects in amplitude and frequency domain of a train measured by an IMU mounted inside the cabin [7]. We further presented a navigation method for trains with inertial sensors, where we also filtered the high-frequency vibrations as good as possible from the train motion with low frequency [8]. In this paper, we propose navigation methods, where we make use of the information contained in vibration measurements. The vibrations are now desired, and instead of suppressing, we separate these high-frequency vibrations in the frequency band from the low-frequency train motion.

We analyze the speed dependency of the vertical acceleration measurements and we can infer speed and position from vibrations only. Despite the navigation purpose, the wheel size can be monitored for onboard diagnostics and maintenance monitoring.

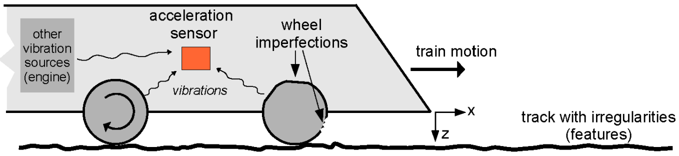

Fig. 1. An acceleration sensor onboard a moving train measures vibrations caused by the wheels, the track and other vibration sources such as the engine.

II. VIBRATION ANALYSIS

A. Inertial data set

The inertial data was captured with a MEMS (micro-electro-mechanical system) IMU (inertial measurement unit) of type "Xsens MTx" with a sample rate of 100Hz. The sensor was mounted inside the train cabin and attached to the overhead hat rack for simplicity reasons. Furthermore, a GNSS (global navigation satellite system) device was installed to record position, speed and time. The diesel powered regional train of type "Integral" can reach up to 160km/h with a maximum of 364 passengers [9]. The measurements were recorded at a normal passenger service operation on a track network in the Munich area, Germany. The data set contains two train runs from Munich over Holzkirchen to Lenggries and three runs from Lenggries to Munich. Two runs are from Munich over Holzkirchen to Osterhofen and two runs reverse. For the data analysis, we choose the acceleration signal with the strongest information content, which is the vertical (Z) acceleration. Alternatively, a single acceleration sensor would be sufficient. It should be noted, that the diesel engine frequency is almost constant over speed because of the hydraulic torque converter transmission system.

B. Vibration analysis plot

We discovered the vibratory navigation information in analysis plots of speed over the acceleration frequency spectrum. In these plots, speed dependent and independent frequencies can be identified. The result of all runs is shown in Figure 2 of vertical axis ”Z”. The X and Y accelerations show as well some speed dependency. The plots are achieved by the following steps by well known signal processing methods [10]:

(a) First, the measurements are divided in sequences of 1024 samples. At a sampling rate of 100 Hz, the sequences have a length of 10,24s.
(b) The second step calculates the power spectral density (PSD) of each sequence.
(c) Each PSD is sorted by its mean GNSS speed measurement in a speed bin. There are 150 bins of $1\,\mathrm{km/h}$ width. If a bin contains multiple PSDs, an average PSD is computed.

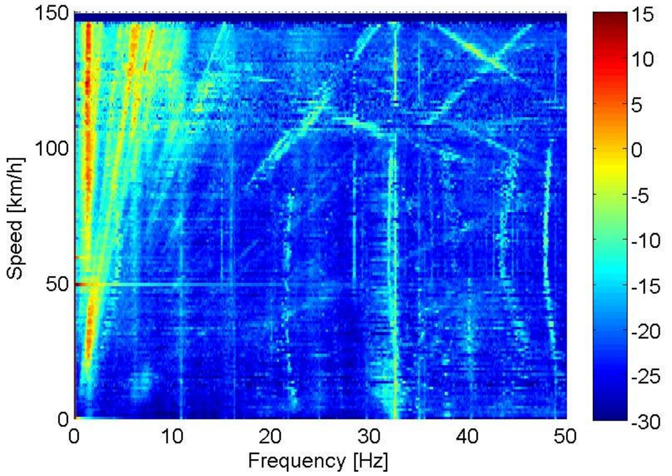

Fig. 2. Spectrograph: vehicle speed over ’Z’ acceleration frequency spectrum.

In this speed spectrogram plot, we can observe several spectral lines. There are vertical lines, which show speed independency as well as several spectral lines through the origin, which show a linear dependency on speed.

The speed independent lines or vibrations arise periodically from engine and power train at 11Hz, 22Hz and especially at 33Hz. The engine vibrations were also observed in [7], in which a scenario is shown of engines running and switched off of a standing train. The train ”Integral” has a special drive system, were a hydraulic torque converter transmission keeps the diesel engine at constant revolutions. The strongest signal lies on the 0Hz (DC) line and is the gravity measurement. There are also strong signals between to 1 and 2Hz where the slow dynamic changes of train motion are observed. Other speed independent vibration sources are theoretically possible from motor driven equipment such as fans, or passengers and cargo (baggage) in motion.

There are spectral lines with a negative speed dependency in the upper right corner. This is an aliasing effect due to the sampling rate (f_s=100Hz), for vibration frequencies more than the Nyquist frequency ($\frac{1}{2}f_s$=50Hz), and will be ignored in the further methods. We focus on spectral lines with positive speed dependency, which can be characterized by two different basic oscillations and their harmonics. The two different basic oscillations arise from the wheels and the track signature as shown in 1. The train ”Integral” has eight axes in total, but the measurements were recorded near two axes and approximately $18\mathrm{m}$ away from the next wheel set. We assume negligible influence of the other wheel sets. Figure 3 shows a simple train model with wheel distance D and wheel diameter d. We present two simple models of periodic vibration and their n-th harmonics for the wheel influence as vibration source. The first equation shows the relation of train speed v [m/s], wheel distance D [m] and acceleration frequency F of n-th harmonic:

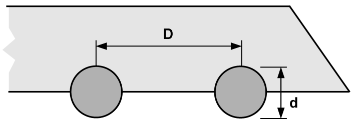

Fig. 3. Simple vehicle model by wheel diameter d and distance D.

$$F_n = \frac{v}{D}n. \tag{1}$$

The second equation shows a relation of velocity, wheel diameter d [m] and acceleration frequency f of n-th harmonic:

$$f_n = \frac{v}{d \cdot \pi}n. \tag{2}$$

Any track signature or location dependent vibratory track feature will affect the first wheel with a shock and after a certain time the second wheel with a shock. The time between the two shocks depend on wheel distance D and speed v. Figure 4 shows theoretical expected vibrations with new wheel diameter ($d = 0.84\mathrm{m}$), a wheel diameter at end-of-life (EOL) ($d = 0.78\mathrm{m}$) and wheel distance ($D = 4.7\mathrm{m}$) [9]. It is possible to recognize the theoretical spectral lines in the vibration

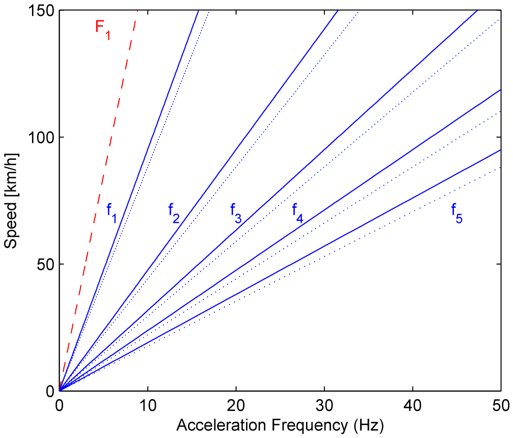

Fig. 4. Theoretical expected spectral lines based on wheels distance $D = 4.7\mathrm{m}$ (red) and wheel diameters $d_{\mathrm{new}} = 0.84\mathrm{m}$ (blue solid) and $d_{\mathrm{EOL}} = 0.78\mathrm{m}$ (blue points).

spectrum of Figure 2. The additional positive speed dependent spectral lines in the upper left part of Figure 2 could result to gear wheels with different sizes and rotational speeds.

III. MEASUREMENT METHODS

The vibrations of interest are the speed dependent, so we propose filters in order to remove the speed independent signals. The spectral components of the slow train motion near DC are filtered by a high pass, and the engine noise is filtered by notch filters at 11Hz, 22Hz, 33Hz. If the engine revolutions varies with vehicle speed, a synchronized multi notch filter would be needed. This allows us to isolate the speed dependent signals for vehicle speed and the localization computation.

A. Speed computation

The actual vehicle speed can be computed from the filtered vibrations in multiple ways, using either the signals based on wheel distance or on wheel diameter or both. We propose a simple method by multiple band-pass filters. For a each hypothetical speed $\hat{v}$, there are band-pass filters designed for every harmonic with the center frequencies F_1 by (1) and/or for f_1, f_2, f_3 by (2). A sequence of the acceleration signal A(k) (e.g. 100 samples) is filtered by this multi band-pass filter with all discrete speed hypotheses $\hat{v}$ (e.g. 150 hypothesis):

$$\hat{A}_{\hat{v}}(k) = f_{\text{bandpass}}(A(k), \hat{v}). \tag{3}$$

In a second step the energy of the filtered signal of every speed hypothesis $\hat{v}$ is computed:

$$E_{\hat{v}} = \sum_{n=-\infty}^{\infty} \hat{A}_{\hat{v}}(n)^2. \tag{4}$$

Finally the speed hypothesis with the maximum signal energy is searched:

$$v = \arg\max_{\hat{v}} E_{\hat{v}}. \tag{5}$$

B. Wheel monitoring

As shown in (2), the vibration frequency harmonics depend on the wheel diameter and velocity. The wheel is now monitored by its diameter for maintenance. A new wheel of the "Integral" has a diameter of 840mm and a worn out wheel at the end of life has 780mm [9]. Translated in vibrations at 150km/h, the new wheel has the first harmonic at 15.8Hz and a EOL wheel at 17.0Hz. An indicator for the train driver can show the actual status of the wear, or alert if necessary.

C. Localization method

A railway track network exists of several tracks R. The location of a train in the network is defined by a track identifier R and a metric 1-D position s on that track. A train path is a trajectory or train run of a certain length and can comprise several tracks. It is defined by an actual location, start location or trajectory length and the sequence of tracks, the train has taken. The vibration signal contains location dependent information when the track signature exitates the moving vehicle. The vibrations based on the wheels distance are ideal to isolate the location dependent vibrations from the other vehicle vibration sources. The method contains four basic steps:

(a) Signal preprocessing
(b) Recording of reference signal and a track map
(c) Correlation of the actual signal with the reference signals of the track hypothesis
(d) Localization computation from correlation maximum

Step 2) is needed for mapping, the localization processing is included in steps 3) and 4). Step 1) is the basis for mapping as well as localization.

1) Signal preprocessing: The data set is preprocessed in order to isolate the vibratory track features. Different train runs with different speeds, cause different time signals for the same track signature. The track signatures are dependent on the location, so a spatial representation of the signal is desired. A transformation of the signal $A(k)$ by discrete time samples k to a spatial signal $A(s)$ by location samples s can be achieved by interpolation:

$$A(s) = f_{\text{interp}}(k, A(k), s). \tag{6}$$

The signal is now in the spatial domain, i.e. the samples are now based on a constant metric distance. The vibratory track features take effect on the leading wheels and rear wheels in relation with the wheel distance. We choose the optimal filter, also known as matched filter in order to remove the undesired parts of vibration signal. The impulse response of the matched filter is a signal of two Dirac-delta impulses, separated by the distance of the wheels. The matched filter extracts the desired vibratory signal parts resulting from the wheel distance:

$$\tilde{A}(s) = f_{\text{MF}}(A(s)). \tag{7}$$

The signals contain phase information, which are disadvantageous for further signal correlation. The phase information of a signal is removed by the computation of the signal amplitude envelope, which is the absolute value of the analytical signal [10]. The analytical signal is a complex signal with the original signal as real part and the Hilbert transformation of the signal as imaginary part. The envelope of the spatial vibration signal is:

$$\hat{A}(s) = |\tilde{A}(s) + j \cdot f_{\text{Hilbert}}(\tilde{A}(s))|. \tag{8}$$

2) Track map recording: Before the signals can be processed, an initial run is needed to record the reference data set in combination with the position on a known track. This can be achieved by additional sensors such as GNSS, a track map, odometers and the accelerometer for the reference data. The vibration reference data is preprocessed by (6)-(8) and stored in the track map.

3) Correlation: The correlation method compares vibration signals of two trajectories or train paths in spatial domain, the last measured vector and a hypothesis vector. The first signal $\hat{Z}_{\text{path}}(s)$ is the vibration measurement vector from the actual traveled path transformed into spatial domain by (6)-(8). The second signal is a reference vibration vector $\hat{A}_{\text{hypo}}(s)$ from the track map of a path hypothesis. Each hypothesis vector contains a possible path of a train in the track network and is usually much longer than the measurement vector. Dependent on the weak signal to noise ratio, a long measurement vector with L samples and a length of 1km to 10km is necessary for the correlation in order to get reliable results. The correlation of the signals $\hat{Z}_{\text{path}}(s)$ and $\hat{A}_{\text{hypo}}(s)$ is defined by:

$$C_{\text{hypo}}(s) = \sum_{m=1}^{L} \left(\hat{Z}_{\text{path}}(m) \cdot \hat{A}_{\text{hypo}}(s+m) \right). \tag{9}$$

The resulting correlation shows a slow changing but significant bias. For further location extraction, the signal is subtracted with the filtered signal precessed by a moving average:

$$\tilde{C}_{\text{hypo}}(s) = C_{\text{hypo}}(s) - f_{\text{MA}}(C_{\text{hypo}}(s)). \tag{10}$$

4) Localization computation: The generated signal $\tilde{C}_{\text{hypo}}(s)$ with the true path hypothesis shows now a peak at the position match $\tilde{s}$. The train location can be computed in different ways. The simplest method is a search for the maximum of the correlation function for each path hypothesis:

$$C_{\text{ML}} = \arg\max_{\text{hypo}} \tilde{C}_{\text{hypo}}(s), \tag{11}$$

The position $\tilde{s}$ in the path is found by:

$$\tilde{s} = \arg\max_{s} \tilde{C}_{\text{ML}}(s). \tag{12}$$

The train location of track R and position s is calculated from the most likely path C_{ML}, the path position $\tilde{s}$ and the track map.

IV. RESULTS

A. Speed measurement

Figure 5 shows the signal energy of the bandpass filters $f1$, $f2$ and $f3$ of the first, second and third harmonic of the wheel diameter dependent vibrations. The pass band is $\pm 0.1\mathrm{Hz}$ around the center frequencies and the stop band is $\pm 0.5\mathrm{Hz}$ with $40\mathrm{dB}$ attenuation. The center frequencies are varied for every speed hypothesis and the signal energy is computed of the filtered signal of 100 samples length (1s). The "total" signal is the energy of the sum of $f1$, $f2$ and $f3$. The reference speed is $101\,^{\mathrm{km}}/_{\mathrm{h}}$, which was measured by GNSS. It is noticeable, that the energy signals show multiple peaks, especially near harmonic fractions of $100\,^{\mathrm{km}}/_{\mathrm{h}}$. The "total" energy signal shows resulting local maxima around $15\,^{\mathrm{km}}/_{\mathrm{h}}$, $25\,^{\mathrm{km}}/_{\mathrm{h}}$, $33\,^{\mathrm{km}}/_{\mathrm{h}}$, $50\,^{\mathrm{km}}/_{\mathrm{h}}$, $66\,^{\mathrm{km}}/_{\mathrm{h}}$, near $75\,^{\mathrm{km}}/_{\mathrm{h}}$, $100\,^{\mathrm{km}}/_{\mathrm{h}}$, $133\,^{\mathrm{km}}/_{\mathrm{h}}$ and $150\,^{\mathrm{km}}/_{\mathrm{h}}$. At the true speed, $f1$, $f2$ and $f3$ show a local maxima, while other speed hypotheses show no matching local maxima of all three harmonics. The wheel diameter is assumed by $0.84\mathrm{m}$ and the resolution is $1\,^{\mathrm{km}}/_{\mathrm{h}}$ of this method.

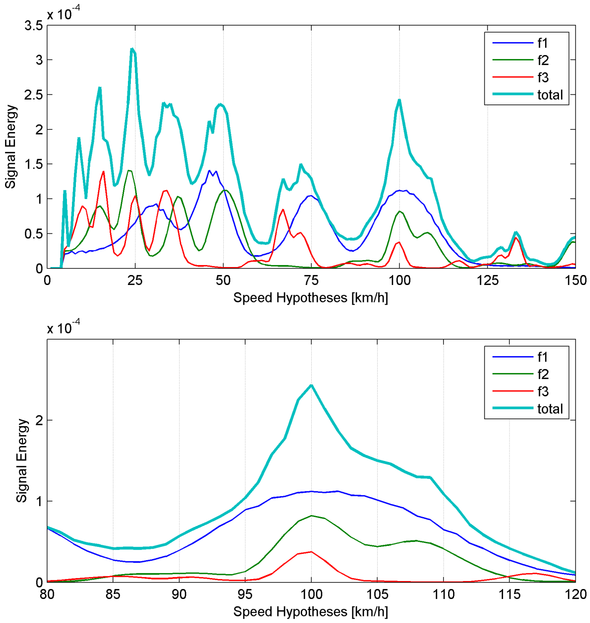

Fig. 5. [TOP] Signal energy over the speed hypotheses for the bandpass filters. [BOTTOM] Zoomed result.

B. Wheel diameter

The wheel diameter estimation result is shown in Figure 6. The measurement vector for this plot is 1000 samples at a speed around $100\,^{\mathrm{km}}/_{\mathrm{h}}$, which is $10s$ of data ($278m$, approx. 330 to 358 wheel revolutions) . All bandpass filters show a maximum at $0.84\mathrm{m}$, which represents a new wheel.

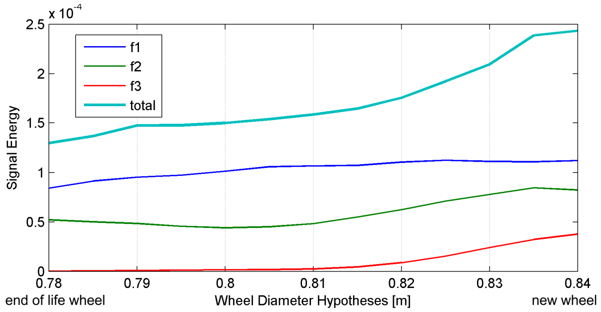

Fig. 6. Signal energy over the wheel diameter hypotheses for each harmonic and the total energy from a end-of-life wheel diameter to a new wheel.

C. Localization

In this experiment two hypotheses are generated for the location estimation, as shown in Figure 7. The true position is at $47.0\mathrm{km}$ from Munich on track 3 (hypothesis A) to Osterhofen. Figure 8 shows the correlation result of measurement vector signal with a trajectory length of $10\mathrm{km}$ at the position $47.0\mathrm{km}$ of a Munich to Osterhofen run with a reference signal of a *different run* of the same path. The localization method outputs a maximum signal for the filtered cross correlation signal around $47\mathrm{km}$ with a good separation to other locations. The filtered signal shows a difference of about $13\mathrm{m}$ to the reference position of $47.0\mathrm{km}$. It should be noticed, that the position for the reference run was recorded by non-differential GNSS, which consequences also position error. Figure 9 shows the result of a train positioned on the same reference position $47.0\mathrm{km}$ at a track 3, but processed with the track hypothesis B. Comparing Figure 8 and Figure 9, the correlation peak disappears now. The correct track can be resolved by searching the global maximum of the correlations results of all hypothetical tracks.

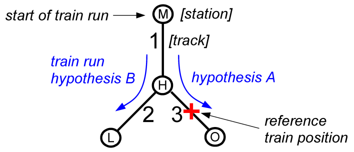

Fig. 7. Train run hypothesis A: Munich over Holzkirchen to Lenggries and hypothesis B: Munich over Holzkirchen to Osterhofen.

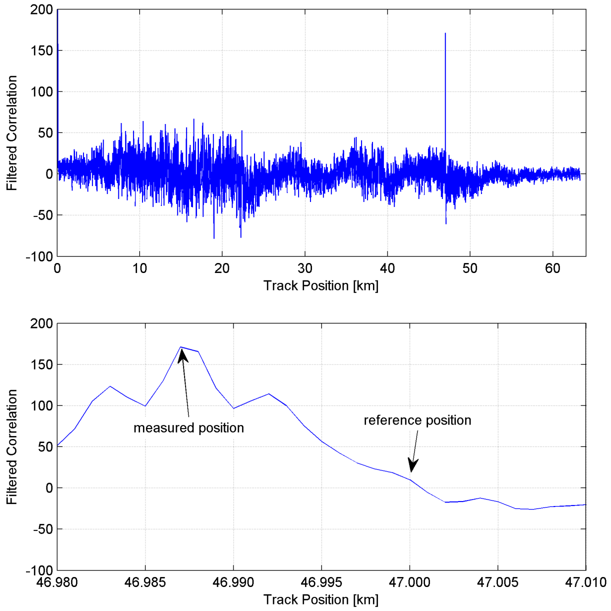

Fig. 8. [TOP] Vibration based localization result (hypothesis A). [BOTTOM] Zoomed result.

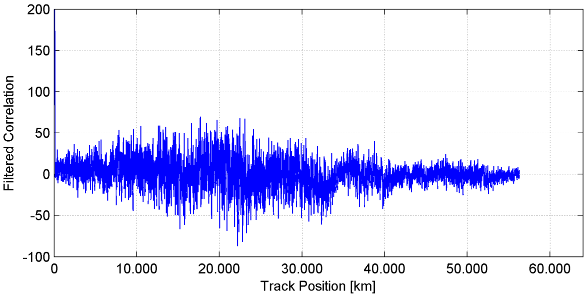

Fig. 9. Correlation results of different tracks (hypothesis B).

V. DISCUSSIONS

A. Speed measurement

The evaluation of each of the first three harmonics and the total energy of the diameter based vibrations showed ambiguity, and the true speed as only local maxima. The resolution of this measurement is $1\,{}^{\mathrm{km}}\!/\!_{\mathrm{h}}$ for an averaged time of $1\mathrm{s}$ (100 samples). The forth harmonic of diameter based vibrations was not used, as there are aliasing effects above $75\,{}^{\mathrm{km}}\!/\!_{\mathrm{h}}$ due to the limited sampling resolution. The evaluation of lower vehicle speeds below $100\,{}^{\mathrm{km}}\!/\!_{\mathrm{h}}$ shows high ambiguity and poor results in most cases. The analysis is very sensitive on the pre-filters for the partially strong signals of the speed independent vibrations. Further improvements of this method are neccessary. Compared to the well known integration of x-axis acceleration, in which relative speed computation suffers from a linear error growth with time, the vibration based method is an absolute approach.

B. Wheel diameter

The sensor was mounted in the vicinity of four wheels and measures different wheels. We supposed, that all wheels have the same wear. We did not measure the true wheel diameters, so the result shows only an estimate and cannot be verified. The wheel diameter meaasurement is not so critical in time, and can be observed over long intervals up to several days.

C. Localization

We have shown, that a track-selective train localization based on vibrations is possible, and able to localize by track and path position. The resolution is here $1\mathrm{m}$. The correlation lengths of the localization procedure are 10km in order to receive enough signal power for a robust maximum. This fact may result in some parts due to the mounting position on the hat rack. On the other hand, we could prove the robustness of this method, as the evaluation of the train location is still possible from this disadvantageous measurement condition. Compared to the well known double integration of x-axis acceleration, in which relative position computation suffers from quadratic error growth with time, this vibration based speed method is an absolute localization approach.

D. Methodology review

The vibration concept works for *exclusive onboard navigation* approaches. A vehicle specific signal filter for the engine vibrations is needed, the distance of the wheels must be known and a reference map is needed for the localization. The creation of the reference map, and the engine filter design will induce some cost. However, from these results, the proposed methods are not suitable as a standalone localization approach.

The key benefits for the vehicle vibration based methodology are the following: At first, the methodology is *independent* from other measurements of existing localization approaches (e.g. GNSS, low frequent IMU or Camera). Further, the correct track can be identified after passing switches. The proposed methods work also in tunnels or underground and are most likely independent from weather conditions, as the sensor is mounted inside the train. The vehicle speed and localization measurements are *absolute measurements*, *track-selective* and can be used to augment strapdown navigation approaches by limiting drift during GNSS outages. As an add-on to state-of-the-art navigation systems with installed acceleration sensors, this methodology requires no additional hardware and can therefore be considered as *low cost* approach in terms of hardware. In the case, an extra acceleration sensor is used, it can be easily mounted to the vehicle structure by cable wraps or screws, so the *installation complexity* is relatively low. On the other hand, a high *installation flexibility* is given, as it will work with mounting positions less complicated and less rough as the undercarriage. Although it is beneficial to be as near as possible at the vibration sources, i.e. the wheels, in order to measure with the best signal to noise ratio.

E. Improvements

As this paper shows basic principles for location and velocity measurement based on vibrations, there exists a large potential of enhancements.

1) Speed and wheel diameter measurements: We consider six advancements for an improved signal to noise ratio:

(a) An enhanced pre-filter, for filtering engine and other vehicle specific vibrations.

(b) An optimized sensor placing, where the measurements are recorded at the nearest possible position to an axle (e.g. on the boogie).
(c) A higher sampling frequency for sampling higher harmonics of the wheel vibrations (e.g. 1kHz and higher).
(d) Additional vibration measurements from orthogonal measurement axes (e.g. X and Y axis of vehicle, additional to Z) in a combined approach.
(e) Other speed hypothesis filter (e.g. wavelet analysis [11])
(f) Tracking of the speed hypothesis (also multiple speed hypotheses in the case of ambiguity)

2) Localization: The localization methods can be enhanced by a sensor placing between two wheel axes and higher sample rate. An approach for tracking the position can be considered by a delay locked loop (DLL) which tracks the output of the correlator, similar to DLLs used in GNSS receivers [12]. Alternatively, if an estimation filter is used for localization, a likelihood function can be generated from the correlation results for a measurement update of particle filters (e.g. directly by the multi modal correlation result) or Kalman based filters.

3) Multisensor fusion approach: Rather than using the proposed vibration methods as standalone approach, a combined information fusion approach with multiple sensor sources and estimation filters can be used to improve the speed and localization results. Suitable sensors are GNSS, odometry, magnetic field sensors with or without active field generation, camera vision, radar and lidar sensors. In [8], we proposed a train localization method based on the train acceleration and turn rates arising from the track geometry and a train motion. The dominant frequencies of the designed and desired track geometry effects, such are curves changes, bank changes and slope changes are below 2 Hz [7] at a train cabin in motion. The vibratory effects occur at higher frequencies and can be separated by a frequency splitter for independency of the measurements. The different approaches can be combined with estimation filters, such as Kalman, grid or particle filters for localization, mapping or simultaneous localization and mapping (SLAM) [13].

F. Variations of the vibration based navigation method

A further extension is possible in a frequency range by using a microphone as a sensor. Current smart phone devices have all necessary sensors embedded (GNSS, acceleration sensors) and can monitor vibrations as long as a good physical contact to the vehicle structure (e.g. window) is given.

This study focuses on vibrations which are already present at certain velocities and the proposed methods are considered as passive methods. These methods would also work with actively generated vibrations by manufacturing a structured, or a slightly eccentric wheel, or a structured track.

VI. CONCLUSIONS

The measurements of a vertical mounted acceleration sensor onboard a rail vehicle shows a horizontal vehicle speed dependency of certain frequencies. We explained the speed dependent and independent vibrations with a vehicle parametric model of wheel size and wheel distance. We showed an approach for absolute location, absolute speed and wheel diameter monitoring, based on vehicle vibrations. The localization is approached by a matched filter, derived from wheelbase and actual speed, and by correlation with a another, prior recorded vibration signal in spatial domain.

The vehicle vibration based concept shows promising first results even with a suboptimal sensor placing (hat rack) and data sampling rate.

The proposed approach can improve existing (onboard) localization approaches for further robustness by improved redundancy and independent measurements in safety critical navigation applications. Especially the parallel track scenario can be resolved for a track-selective localization. We identified possible benefits of absolute measurements in terms of speed and track-selective location, low hardware cost, relative high flexibility and relative low complexity in terms of installation.

In addition to use vehicle vibrations for navigation, other signals might be considerable and we conclude in a more general way: Every measurable signal which contains location depended information is suitable for navigation, provided that there is a methodology to extract this information.

After proofing the concept for trains, a very interesting research question arises from this study: "Are the proposed navigation and monitoring methods transferable to automotive vehicles?"

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