Operational Experiences with Onboard Diagnosis System for High Speed Trains

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1. INTRODUCTION

The primary objective of the project “Onboard diagnosis system for high-speed trains” is to guarantee the high availability of InterCity-Express (ICE) trains during the whole lifetime using condition based maintenance procedures. This ensures also a significant improvement of operational safety of railway vehicles. The detailed specification of an InterCity-Express onboard diagnosis system requires therefore the establishment of broad basis of data and knowledge to determine appropriate sensor positions, measuring principles, assessment algorithms and failure-specific features.

Condition monitoring algorithms were tested by failure simulations with ICE trailers on the track. A prototype onboard diagnosis system was specified, realised and installed – operational experiences and lessons learned will be presented.

2. SCOPE OF ICE ONBOARD DIAGNOSIS

As a subcontractor of Deutsche Bahn AG, ISTec started in 1999 with generic investigations on incipient failure detection methods for high speed trains. One issue of this contract was a certain know-how transfer from diagnosis systems developed for pump and turbines in nuclear technology to InterCity Express vehicles.

From the early beginning it was evident, that there were basic differences between pumps and trains concerning the excitation functions: Stationary operating machines normally are forced by random and steady-state excitations, trains in operation are affected by a mixture of non-linear excitations and transient effects like impacts from the track. Furthermore, trains are running with different speeds on different roadways. Common denominator from set-point of failure diagnostics is in both cases a mechanical multi-mass system with mass-distribution, material stiffness and damping ratio which can be forced to show reactions like noise, sound and vibration - which will be from characteristic nature for the monitored components itself. To extract these baseline reactions like a finger-print for “health-conditions” and to monitor these features during the whole operation of the system is one fundamental objective of such a project.

As well established in machinery monitoring technology, the scope of application was focussed to ICE-trains with concentration to the bogie-construction, but also the whole trailer should be addressed. Therefore, the monitoring components are chassis frame with wheel set, suspension units and dampers as well as roller bearings, wheel treads and shafts, specific cantilever constructions and the overall vehicle structure.

The main issues can be divided in different levels, corresponding to safety and availability aspects: The graph in figure 1 illustrates the hierarchic structure of onboard diagnosis in three levels: The component protection level has the highest priority, which directly intervenes with train operation in case of derailment (onboard alarm). The second level concerns issues related to the dynamic stability, i.e. detection of function losses of so-called stabilizing systems with online information to the conductor (onboard alert). The availability level addresses the condition-based maintenance after detection of wear-induced changes.
A basic difference between this type of online monitoring and “normal” protection systems is the nature of alarm set points which are not determined by maximal acceptable loads or amplitudes but by the intention to detect any anomaly via pre-alerts in an incipient stage to enable countermeasures or pre-planned inspections without stress in due time.

As mentioned before, onboard diagnosis shall address the whole “ICE family” covering ICE-1/ICE-2/ICE-3/ICE-T. Therefore, a general platform concept should be developed. However, the start of investigations was done with ICE-2 trailer type as a baseline.

3 BASELINE MEASUREMENTS AND FAILURE SIMULATIONS

Concerning the scope of investigations as well as the data acquisition hardware since 1999, activities can be divided in three phases.

3.1 ROLLER RIG INVESTIGATIONS

At first, a signal acquisition system was defined and assembled: Numerous sensors were mounted to a bogie of an ICE-2 passenger trailer to gain measuring data at the roller rig of the Research and Technology Centre FTZ (Forschungs- und Technologiezentrum) in Munich-Freimann. The investigation focussed on the driving behaviour with slightly damaged components and different excitation functions.

In figure 2 the instrumentation concept for one bogie is documented: Up to 15 measuring locations had been defined, where triaxial accelerometer sensors had been mounted. In addition with microphones and absolute displacement sensors a total of 70 signal channels in parallel was available and stored on magnetic tape during various experiments. The stored frequency content was up to 20 kHz.

First goal of these investigations was the interpretation of natural frequencies of an ICE-2 trailer. Therefore, the roller rig excitations varied in broad manner: Sine-sweep excitations, pulse excitations in various directions, random noise excitations, simulated track excitations covering measured time records and combination of several functions. The speed varied between 0 and 280 km/h, track-alignment and conicity also changed.

In a second step, operational tests with slightly damaged components were performed. Failure simulations concentrated on wheel tread wear, non-circular wheels, flat spots on wheel tread, roller bearings without lubrication, worn wheel set guiding sleeves, anti-rolling dampers with malfunctions etc..

The signal analysis task was done offline at ISTec diagnosis laboratory, covering correlation in time- and frequency domain as well as statistical discriminants.

3.2 ONBOARD MEASURING AND ASSESSMENT SYSTEM (MAS)

After roller rig test had been finished, the sensors and signal recording technique was adapted to another ICE-2 trailer for measuring journeys performed without passengers.

An important objective of these journeys was to gain data with real excitations from the track to determine the actual operational behaviour with intact or slightly damaged components. Subsequent to the measurements, the data were evaluated to develop algorithms for online failure detection.

As documented in figure 3, the sensor distribution was in principle comparable to the situation on the roller rig. To take into consideration the environmental conditions during train operation, all sensors and cables had to be shielded for this long-term investigations. Data conditioning and acquisition was installed in the lavatory of one 2\textsuperscript{nd} class passenger trailer.
The data acquisition unit was active only for specific failure simulation experiments like damper malfunctions, wear at guiding sleeves or wheel tread. However, sensors including preamplifier electronics were tested over a 18 months period, covering journeys with total of 800,000 km distance on the track.

During this period, only one sensor failed due to resistance problems with plug adapter. Therefore, these measurement campaigns also delivered practical experiments with long-term stability of sensors, associated electronics, cables, attachment flanges and fitting plates.

All relevant findings of investigations on roller rig and onsite on the track were input for a feasibility study “Development of incipient failure detection system for bogie monitoring of high speed trains” /1/ finished at the end of 1999.

3.3 RAILWAY CONDITION MONITORING SYSTEM (RW COMOS)

All relevant findings of the above mentioned study were subsequent implemented into a prototype system which was developed and installed in another trailer of the ICE-2 train in November 2000. Since April 2001, this kind of prototype system is running in all passenger trailers and the steering car of the selected ICE-2 train. At present, basic design features of this system are (see figure 4):
- Bogie instrumentation reduced to six accelerometer sensors, two sensors at absorber cantilever position.
- Temperature sensors are included in some of accelerometer casings.
- Sensors are MIL-standard protected.
- Cables are shielded within bend-pipes.
- Diagnosis units are positioned in electronic bays of ICE-2 trailers.
- Diagnosis units are running self-sufficient without signature-interference to other trailers.
- Individual systems are connected via local network to DAVID onboard computer system.

4 DATA ANALYSIS USING DIFFERENT ALGORITHM

An important objective of these journeys was the collection of appropriate data to compare real operational behaviour on the track with intact or slightly damaged components. The dynamic signal part of accelerometer sensors offers a lot of status information applying more sophisticated signal analysis methods like crest factor analysis, histogram analysis, correlation/coherence analysis, spectral density analysis, phase analysis, statistical moments etc.. As the measured data show distinct reactions to simulated failures confirming the feasibility for early detection of functional degradation or component wear, it is possible to optimise feature extraction in relation to basic failure types /2/.

4.1 INVESTIGATIONS IN TIME DOMAIN

The information content of strip charts offers various information – but primarily from the point of excitation functions. In figure 5 time records of bearing probes are presented over a 17 minutes journey: On the bottom of the graph the train speed is documented, above time patterns of four acceleration sensors on bearing positions are summarised. There is evident a strong relation between speed and acceleration, furthermore a lot of distinct influences from track conditions are superposed: Impacts can be related to rail profile, deviations, track alignment but also to influences of tunnels and bridges. The acceleration level at bearing positions is relative high – maximum was above 1000 m/s\(^2\) in z-direction. After the first and second stage of suspension, realised by coil springs respectively pneumatic cushioning, the levels are reduced by factor 10 at each stage. Accelerations are strongly dependent on track conditions and speed: In figure 5, upper right, a comparison between various measurements in deviation areas (speed < 100 km/h), curved track (speed < 100 km/h) and high speed on straight track (280 km/h) shows remarkable differences, even in x-, y- and z-directions.

Compared to this sensitivity for excitation functions, characteristic influences from the vehicle itself are hidden behind these dominant effects. Therefore time domain analyses are well-suited for the detection of contact problems wheel/track and can be used for derailment monitoring.
In general, signal assessment in time domain is not a time consuming job and shows spontaneous feedback after several milliseconds. The algorithms used in RW COMOS are peak-level monitoring, crest-factor monitoring and histogram analysis.

4.2 INVESTIGATIONS WITH STATISTICAL DISCRIMINANTS

From technical point of view, various discriminants and statistical moments can be used for incipient failure detection methods. Our investigations proved the diagnostic feature of the fourth statistical moment for monitoring tasks like incipient defects on roller bearings or coupling heads. Note that the central moment of order $k$ of a distribution is defined as:

\[ m_k = E(x - \mu)^k \]

The second central moment is the so-called “variance”. The third moment is the “skewness” which is a measure of the asymmetry of the data around the sample mean. The skewness of a distribution is defined as:

\[ y = \frac{E(x - \mu)^3}{\sigma^3} \]

The fourth moment is called “Kurtosis”, which is a measure of how outlier-prone a distribution is. The Kurtosis of a distribution is defined as

\[ k = \frac{E(x - \mu)^4}{\sigma^4} \]

The Kurtosis of the normal distribution is 3. Distributions that are more outlier-prone than the normal distribution have Kurtosis greater than 3; distributions that are less outlier-prone have Kurtosis less than 3.

In figure 6 the use of Kurtosis is demonstrated with different flats on wheel treads: One wheel showed four smooth (artificial) flats at 90 degrees surrounding positions, a second wheel was tested with one strong flat: Whereas the wheel/track-interaction with 4 smooth flats showed no reaction in time domain and stable Kurtosis level of 3 (figure 6, lower left), contact problems of the strong flat wheel caused impacts in the strip chart records as well as a strong increase in average Kurtosis levels up to 15 (figure 6, lower right).

As the calculation of variance needs less than 1 second, a certain averaging procedure is implemented for Kurtosis calculation to suppress singular false alarms from deviations etc.. A typical reaction time for statistical discriminants was defined to 30 seconds. Derived from additional investigations with failure simulations, reactions from wheel treads are in the low frequency domain, on contrary bearing problems typical show high frequency characteristics. Therefore, two Kurtosis functions are needed: Divided by filter techniques we use so-called “lowband-Kurtosis”, convenient for wheel tread failures and “highband-Kurtosis”, sensitive for roller bearing damages.

4.3 INVESTIGATIONS IN FREQUENCY DOMAIN

In frequency domain, natural frequencies of the mechanical coupled multi-mass system of trailer, bogie and wheel set can be identified using correlation analysis. The basic principle is demonstrated in figure 7:

Starting with a pre-selected set of sensors - shown in figure 7, lower right - between relevant sensor pairs the coherence and phase functions are calculated. If the coherence of a selected peak structure in the spectra is rather high - respectively above 0.7 - a identical source of vibration is presupposition for the analysed phenomena. If a set of cross-pair coherence functions is calculated, the associated phase combinations offer relevant information concerning mode shape of vibration.

The correlation matrix in figure 7 points out the principle of these investigations: in the upper right matrix several coherence spectra are documented in a frequency band from 19 to 32 Hz. In lower left
matrix, associated phase spectra are visible. Four areas of coherence and phase “zooms” are marked in yellow: A high coherence of these selected sensor pairs at 27 Hz confirms in-phase behaviour. In combination with sensor orientation, a specific bending mode shape of the bogie was identified at 27 Hz.

On top of figure 7 other natural frequencies are pointed out: The anti-roller dampers are mounted on cantilever construction. The associated cantilever beam mode was identified by correlation analyses at 84 Hz. The horizontal mode shape of roller bearing housing including the coil spring support construction was related to 16 Hz frequency peak.

Compared to these results further natural frequency peaks could be identified. Due to the averaging procedure in the frequency domain, baseline patterns need constant speed conditions, otherwise the wheel harmonics exhibit frequency shifts. Therefore, a optimisation of certain parameters of Fast Fourier Transformation (FFT) Algorithm was needed, especially the adjustment of frequency resolution, averaging time, average number and overlapping procedures. The minimum averaging time used for monitoring procedure is 30 to 60 seconds.

Investigations in frequency domain show lot of advantages: Full signal dynamic is guaranteed by averaging procedure - stochastic and deterministic influences can be separated. Signal combinations are valid for suppression of short-term alerts, caused by impacts. Natural frequency monitoring is a well-established tool for detection of long-term wear, stress-corrosion degradation and ageing phenomena in mechanical components.

4.4 FEATURE EXTRACTION FOR ONBOARD-MONITORING

A typical example for feature extraction is documented in figure 8: The wheel set guiding sleeve is a major component affecting the dynamic stability of wheel set versus bogie construction: One set of two guiding sleeves is positioned within each coil spring pair of primary suspension unit. As these sleeves are not visible from the outside, they are replaced due to maintenance recommendations after specified operational periods.

From the mechanical point of view, the guiding sleeve is part of the spring support construction of figure 7, upper left. Deviations in geometric dimensions due to wear as well as modifications of stiffness-parameters due to ageing phenomena may affect the dynamic properties of guiding sleeves as well as the natural frequency of the mentioned support construction as a whole.

Failure simulations with wheel set guiding sleeves were prepared by decreasing the outer diameter by 0.7 mm. In figure 8, lower part, a waterfall-representation of spectra in 0 – 200 Hz domain is documented. The used sensor was mounted nearby the bearing construction (similar to figure 4, upper right). The dotted curve in figure 8 indicates the running speed component of the wheel set. In the upper part of figure 8 roller rig simulations are compared with onboard simulations: Blue spectra represent reference conditions, red spectra are associated with “abnormal conditions” during the above mentioned failure simulations. Although the roller rig excitation functions are not completely comparable to onboard simulations on the track, the increase of the 16 Hz frequency component is obvious in both cases - marked by red arrows. On real track the conicity leads to stronger sine excitation at 7 Hz domain.

Based on verified baseline investigations, this example underlines in excellent manner the signal oriented monitoring procedure via FFT techniques and frequency selected features for onboard diagnostics.

5. ONBOARD DIAGNOSIS SYSTEM

Primary goal of an onboard system for railways is a strong contribution to increased availability and improved economy of the system concerned. In parallel safety related applications are addressed by the basic principle for early detection of incipient failures. This kind of condition monitoring for trains
is based on general findings: Measured quantities carry an implicit information on phenomena or parameters that induce the system transfer function. The system output - monitored with sensors at various locations - enables a signature based interpretation as soon as anomalies or changes in signal characteristics occur /3/.

The onboard system RW COMOS therefore needs specific features concerning the fundamental analysis tasks of the monitoring concept realised by self-sufficient signal processing units in each trailer, steering car or power car, embedded in powerful data management environment. The following chapters highlight these topics and focus the actual state of lessons learned with this system.

5.1 ANALYSIS AND MONITORING CONCEPTION

The basic observations derived from failure simulations with trains on the track prove, that efficient onboard diagnosis needs different analysis features in parallel. Therefore, a selection was needed, which algorithm combination solves a certain problem. In figure 9 the basic principle is documented:

Failure developments associated with low-damped rotating parts like wheels, shafts and roller bearing are monitored, using time domain analysis methods in combination with statistical discriminants. Frequency domain analyses are used in general offline for additional trouble shooting.

Stabilising elements like suspension units, dampers or guiding sleeves are monitored with selective methods in frequency domain. This also holds true for chassis frames or cantilever constructions: Using natural frequencies of these constructions the pre-alert time-span is rather high.

In connection with clearances between individual parts of the construction - like vehicle frame itself or shock absorption in coupling heads - a combination between analysis methods in time and frequency domain is commendable.

In principle these methods are running with different data samples and averaging features, the algorithms have to be treated in parallel processing units.

5.2 RW COMOS SIGNAL PROCESSING

The system features enable signal acquisition and signal conditioning of 28 input channels. Basically acceleration sensors and/or temperature sensors are used. The real signature processing in time and frequency domain needs sampling rates up to 32 ksamples/s. To fulfil these specifications, a powerful digital signal processor (DSP) was selected. On the other hand, data storage of relevant data over a longer period (maximum time span of 2 years) was specified for offline diagnosis purposes. Due to the high amount of data, a standard data base in connection with PC-techniques was selected too. Therefore, a combination between embedded PC and DSP subsystem is used /4/.

As documented in figure 10, all sensor signals are connected via signal condition unit to input panel of analogue/digital converter (ADC module). Data processing in time and frequency domain as well as statistical processing are main tasks of DSP unit. Data transfer to PC-unit is realised via host-port-interface (HPI) to PC-ISA-bus. This ensures high data transfer capability. Temporary data storage of measured data is done by flash disc, for long-term data storage a hard disc with laptop-architecture is used.

Process control of DSP is triggered by PC via sub-unit for time co-ordination. Data transfer is done in asynchronous manner via HPI communication channels. PC unit is running under Linux operating system. The host communication is needed for bi-directional data transfer/control and configuration set-ups for DSP software.

A first prototype of this system was installed in November 2000 in one ICE-2 trailer car. Meanwhile seven upgraded systems (figure 10, upper part) are running in all passenger trailers of one ICE-2 train.
5.3 LESSONS LEARNED WITH PROTOTYPE SYSTEM

System installation and system operation under realistic conditions during train operation was needed to gather information about rigidity of system hardware (sensors, cables, connection parts, electronics and processing units) and the practical efficiency of data transfer tools, off-line signature processing tools and alert level settings (sensitivity, logic editor, false alarm elimination etc.).

For collection of long-term experience with system hardware, several steps were realised: MAS system was installed in July 1999, so-called Dummy-system (without sensor application) was working as a test stand for RW COMOS electronic components since August 2000. The first prototype of RW COMOS was installed in November 2000, additional systems are in operation since April 2001. Due to this step by step installation, several updates of system features were tested.

To increase the know-how with data handling and software set-ups, the great amount of data is analysed off-line at ISTec-laboratory on a regular basis. For this purpose stored data of RW COMOS are copied every two weeks on CD and analysed in detail. Figure 11 shows examples of condensed data, using specific offline software tools:

In figure 11, upper left, peak level trends of two bearing probes are presented versus train speed variation. This kind of analysis is used for assessment of wheel tread surface condition or roller bearing status control.

Four histogram analyses are presented in the lower part of figure 11 assigned to four dedicated speed classes. From statistical point of view these representations can be used for alert level settings of failures coming up with wheel/track contact problems.

FFT analysis are presented in the upper right of figure 11. For several selected spectra, the deterministic spectra parts like 1x running speed and higher harmonics (2x, 3x...) or speed variable excitation from tie reverberation (dotted triangle) are marked. In addition there are stochastic parts from natural frequencies of specific components visible. The inserted frequency band of interest (FBOI) is corresponding to the above mentioned spring support natural frequency at 16 Hz (see figure 8).

For each specified frequency band amplitude-, frequency- and peak form parameters are calculated. Based on trend analysis of different monitored peaks individual thresholds and alert levels may be specified. In figure 11, upper right, a corresponding FBOI amplitude trend with alert level settings is included.

5.4 DATA MANAGEMENT

According to the hierarchic structure of onboard diagnosis in three levels (documented in figure 1), the data management for improved maintenance in general is highlighted in figure 12:

Each RW COMOS is linked to ZEUS computer of the individual trailer. If alert or alarm level are exceeded, a specific failure code is sent via local area network to DAVID main computer, situated in the power car. Level-1 alarms (so-called component protection level) and Level-2 alerts (so-called operational level, related to dynamic stability situation of the cars) are displayed to the conductor in the steering/power car. In future it is planned that onboard alarm (Level-1) directly intervenes with control device electronics to stop the train in an automatic way. Level-3 failure codes (so-called availability level) are linked via remote control techniques to ICE maintenance data base and ICE maintenance centres /5/.

Below this online data management, a fourth level will be installed for offline data analysis of original signatures. Via direct access to RW COMOS systems in the train, original data will be transferred from hard disc via back-up media to signature data base. The associated data analysis is performed in
ICE competence centres. Due to deep insight in trend data, maintenance recommendations will be defined and advanced signal evaluation tools are developed.

Based on this data base, condition based maintenance will be addressed via early detection of trend developments due to long-term wear, high-cycle fatigue or ageing phenomena. Including specialists for constructional responsibility, logistic improvements like extension of maintenance intervals or input for technical redesign will be in the scope of this system. This combination of online, remote controlled and offline information transfer offers a broad flexibility for man-machine interface and advantages in maintenance technology.

6. CONCLUSIONS

Onboard diagnosis systems for high speed trains improve the safe and efficient operation of railway traffic and are of great logistic importance to install condition based maintenance procedures. Main issues of the presented system can be classified to safety and availability aspects. Therefore, the system information can be divided in online and offline features.

Baseline measurements and realistic failure simulation measures are presuppositions for signature investigation of source term identification caused by high cycle fatigue, ageing effects and wear.

Signal analysis in time and frequency domain - together with statistical assessment - enables a selection and interpretation of monitoring features and algorithm.

The onboard diagnosis system was designed to handle all monitoring tasks with adequate system performance.

Field tests with Dummy-, Prototype- and Upgrade-System increased the rigidity under realistic conditions.

Beneath optimised online features the system conception includes offline data management tools for competence and maintenance centres.

Current activities are concentrated on transfer of basic monitoring principles to other ICE-series demonstrating the platform strategy of the system. Such strategies are of great logistic importance for ICE service centres. The potential for maintenance optimisations in the field of railway traffic is extremely high due to the great number of operated components and vehicles from similar type and design.
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