

# On-line vehicle condition monitoring based on probability approach

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**Abstract** – The paper gives a description of a diagnostic and monitoring system for the first Czech hydrogen-powered bus. The system captures operating characteristics which affect ride quality and mechanical damage of the vehicle. Probabilistic evaluation of data is explained and some interesting results are introduced.

## I. INTRODUCTION

One of the motivations for monitoring the operating characteristics of vehicles is to verify static and dynamic strengths of their structure with respect to long-time in-service loads which often vary considerably with time. The assessment of hydrogen-powered vehicles is more stringent than in that of conventional vehicles [1]. Higher safety requirements result not only from the presence of compressed hydrogen vessels on board of the vehicle but mainly from the vehicle's greater weight and the altered weight distribution.

The purpose of this article is to give a description of an on-board measuring and monitoring system of a hydrogen-powered bus and the method of measurement and processing of data using probabilistic techniques.

## II. HYDROGEN BUS AND MONITORING SYSTEM

The hydrogen powered bus incorporates the body of CITELIS 1B, a low-floor urban bus manufactured by IVECO ČR a.s., a member of the Irisbus Group (Fig. 1). The traction system is based on the concept of ŠKODA Electric trolleybuses.

The main source of energy is a hydrogen PEM fuel cell, while the secondary sources comprise a traction battery and ultracapacitors. Energy flows within the power supply system of the bus motor are optimized by the control system. It enables energy to be recovered and delivered to the secondary sources (e.g. on downward slopes, during braking, etc.) to be reused for energy intensive manoeuvres (e.g. acceleration).

An on-board measuring system has been designed and built for the purpose of continuous recording of measurement readings (and for use in short-time tests). It

was installed to the hydrogen bus as its permanent component.



Fig. 1. Hydrogen-powered bus.

A schematic diagram of this measuring system is presented in Fig. 2. Its core is a Kontron MPCX28R industrial computer.

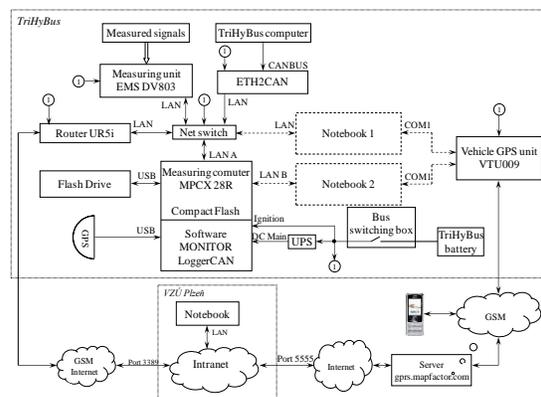


Fig. 2. Schematic diagram of on-board measuring system.

Values of measured physical variables are acquired by the EMS DV 803, a 32-channel data acquisition device manufactured by small firm “Ing. Pohl”, Czech Republic. CAN bus data are logged by the ETH2CAN module from the company CANLAB, Czech Republic. The data acquisition device stores the readings in a CompactFlash memory and transmits them on-line via a network

interface to the MPCX28R Kontron industrial computer. The computer re-calculates the sampled data into statistical values and rainflow matrices which are sent to an FTP server for further processing. The access to the measuring system is available through a mobile network and via an UR5i router.

For system administration and real-time monitoring of measured data, the industrial computer can be accessed via a web interface using the remote desktop function. Only limited time histories can be downloaded through the mobile network. The essential data thus comprise of the statistics and rainflow matrices. Time-history segments which are of interest and importance can be extracted, and reduced if required, from the daily files. They can then be transmitted via the remote desktop by the Monitor application.

The measuring system is fed from the operating battery of the bus. The following sensors are wired to the EMS DV803 data acquisition device:

- a) Four Cressto pressure transmitters installed in the pressurized system of suspension providing for individual wheels,
- b) Microstrain 3DM-GX1 gyroscopic sensor which detects vehicle orientation with respect to three axes,
- c) Acceleration sensors in the top box of the vehicle,
- d) Acceleration sensors on the roof-mounted unit – the hydrogen container frame,
- e) Traction motor speed sensor - two inductive Turck BIM-EM12 EAP sensors which log the distance travelled by the vehicle,
- f) A total of 17 strain gauge sensors in critical locations of the body.

In order to verify the mechanical strength of the vehicle, we focused on those critical structural details that transmit loads from hydrogen system components which are not found in conventional buses. However, some measured locations were chosen on critical details which had been known from experience to be under high stresses. In those, the larger weight and non-standard weight distribution could lead to even higher stress levels. We also explored maximum in-service accelerations and compared those to recommended acceleration levels for hydrogen propulsion components.

### III. DATA EVALUATION

High-cycle fatigue lifetime predictions [2] were obtained using a probabilistic procedure based on nominal values for individual structural details [3]. The nominal (mean) stress level, the notch factor and notch sensitivity must be known for each location. Fatigue strength and the S-N curve shape for the notched location are computed from the fatigue strength of a smooth test piece, taking into account the component size, the surface quality, surface finish, the loading method and other aspects. The S-N curves (limit curves for evaluating high-cycle fatigue) were proposed on the basis of the BS 7608 standard.

The resulting fatigue life distribution function (FLDF) should account for the random natures of loading, as well as the random material properties. The input into the process of FLDF determination consists of the quantity  $s$  of constant-length segments from the loading process, and of 99 life curves for individual failure probability levels. Hence, a total of  $k = s \times 99$  combinations of loads and material properties are available.

The FLDF is obtained by calculating lifetimes for all segments of the loading process one by one, using the lifetime curve for  $P = 1\%$ , then  $2\%$ , and so forth until  $99\%$  is reached. The result is 99 sets of lifetime data. From each set, the lifetime is determined for the probability of occurrence associated with the appropriate lifetime curve. To accomplish this, the FLDF must be evaluated for each lifetime set. The resulting FLDF is in the form of a set of lifetimes for the particular probability of occurrence.

After each cycle, the current fatigue damage level  $D_{cur}$  at the time  $t_{cur}$  is calculated and a new empirical distribution function of fatigue life is determined (Fig. 3). By examining the changes and the shape of the instantaneous FLDF with respect to the design point A, the following relations are obtained [4]:

- a) Probability of premature fracture  $P_{g,p}$  for the required service lifetime  $t_{req}$ ;
  - b) Current probability of survival  $P_{a,surv}$  related to the service time  $t_{cur}$
  - c) Residual fatigue life  $t_{res,p}$  with respect to the required lifetime  $t_{req}$
  - d) Actual residual life with respect to the current FLDF  $t_{res,cur}$ , which is the difference between the time at which the current FLDF corresponds with the failure probability  $P_{allow}$  (inverse function of FLDF) and the current time  $t_{cur}$ .
- During service, the shape and position of the FLDF may change. The shift of the FLDF reflects the evolution of the damage level  $D$ . After the time  $t_{lim}$ , at which the probability of damage  $P_{allow} = 1$ , the failure probability is higher than the allowable value. If we accept reduced safety, we can continue using the vehicle. However, during the continuing operation, a time instant,  $t_0$ , will come at which the probability of survival will become zero.

The shift of and the changes in the shape of the FLDF also alter the values  $\Delta t_g$  and  $\Delta P_g$ . While the critical location is monitored, the above variables as well as their ratios to the originally proposed values ( $t_g/t_{req}$ ,  $P_g/P_{allow}$ ) are evaluated on a continuous basis. Figure 3 illustrates the evolution of the probability of premature failure. The shift of the FLDF towards shorter lifetimes indicates an increasing severity of operating conditions (poorer road surface quality) or changing vehicle condition that leads to higher loads in the monitored location.

The inputs into the data acquisition device include signals from two inductive sensors of traction motor speed. The pulses are evaluated by the data acquisition device itself.

When the bus is stationary (the delay limit can be reprogrammed in the software) and no pulses are received, the devices discontinues the measurement. This saves the data storage capacity and computing time, and eliminates unnecessary data transfers with no information. The data acquisition device offers two data recording modes. In the first mode, all sample values are recorded at the pre-set frequency. In the second mode, only the peaks are committed to memory. The second mode substantially reduces the quantity of the data and is suitable for subsequent decomposition of time histories into series of amplitudes using the rainflow technique.

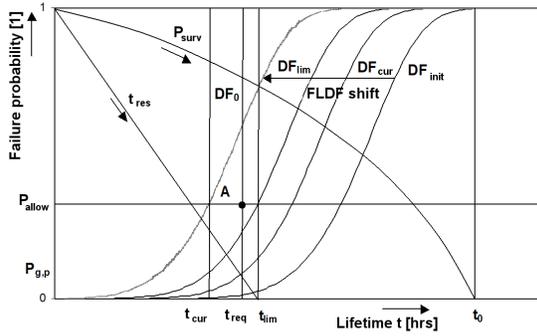


Fig. 3. Evolution of residual life and failure probability during monitoring period of a structural detail.

The Kontron mobile computer runs the application Monitor which saves the measured data to its exchangeable hard disk in regular intervals (approximately 10 seconds). The vehicle speed and the distance travelled are evaluated as well. Figure 4 illustrates the procedure for calculating the FLDF.

The Monitor application can further reduce the data quantity by calculating relevant statistics and rainflow matrices for the channels. The statistical and matrix calculations can be completed at the end of each day, each time the vehicle is parked, or after running a pre-defined distance. Figure 5 shows the distance travelled and how the distance counter is reset after the pre-defined number of kilometres which initiates the calculation of a new rainflow matrix.

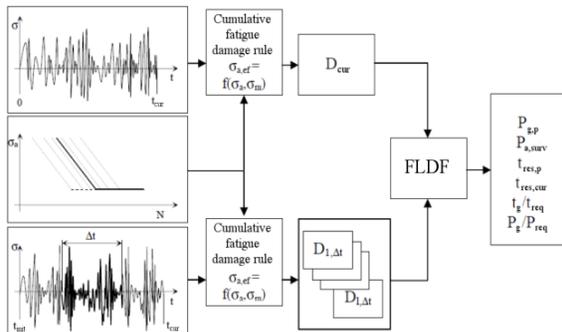


Fig. 4. FLDF calculation procedure for one of the critical details.

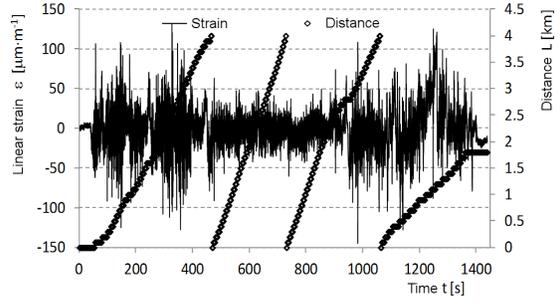


Fig. 5. The travelled distance for which rainflow matrices are calculated from strain-time histories.

As these calculations take place simultaneously with the on-line data transfer from the data acquisition device, they utilize the almost entire computing time capacity of the hardware. The matrices calculated for equal distances make a very useful input into the probabilistic assessment of life and trends of vehicle stresses.

The completed statistics and rainflow matrices are sent automatically to an FTP server housed in the Research and Testing Institute Plzeň where an application uploads them to the memory of the computer which maintains the database of measured data. The database to which the data is fed has been developed in MS Excel environment. It contains updatable S-N curves and their left-hand side tolerance limits for various probabilities of failure occurrence. The probability of survival, residual life and other parameters are evaluated with the aid of the VBA.

#### IV. RESULTS

Long-term monitoring of fatigue damage of the structure of a hydrogen-powered bus revealed that the structural details to which components of the hydrogen propulsion were attached exhibit no significantly increased damage. Paradoxically, the most severe damage was found at the point of attachment of the traction motor. However, this location proved critical in ordinary trolleybuses as well. The shift of the distribution function of fatigue life for this location due to node improvement is shown in Fig. 6.

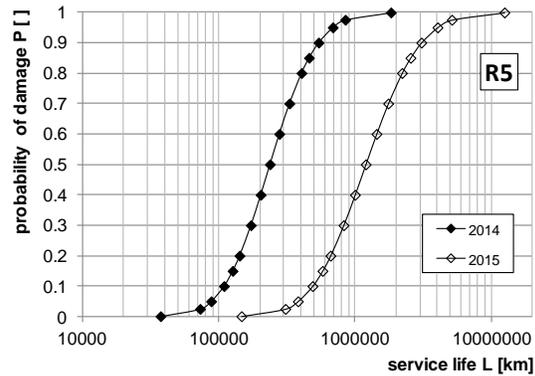


Fig. 6. Shape of the fatigue life distribution function for one of critical structural details.

Figure 7 shows the power spectral density of the transverse component of acceleration measured on the vehicle roof in the vicinity of hydrogen vessels and its comparison with the data measured on ŠKODA Electric 24Tr trolleybus which uses the same basic structure of the IVECO Citelis vehicle as the hydrogen bus. Added to the comparison are values derived from the EN 61 373 standard for vibration testing of electrical equipment of vehicles (and roof-mounted structures). This profile is a result of long-term measurement. The profiles of components of power spectral densities of acceleration are similar to those found in conventional vehicles. However, the transverse acceleration exhibits larger amplitudes than the 24 Tr trolleybus data and the standard values. The resulting standard deviation of transverse acceleration is considerably larger. These findings led to concerns that the conversion of the bus to a hydrogen-powered bus might have impaired the vehicle's stability. However, the subsequent stability tests (severe lane-change manoeuvre according to ISO 3888 1 and the "moose test") did not confirm any such impairment [5].

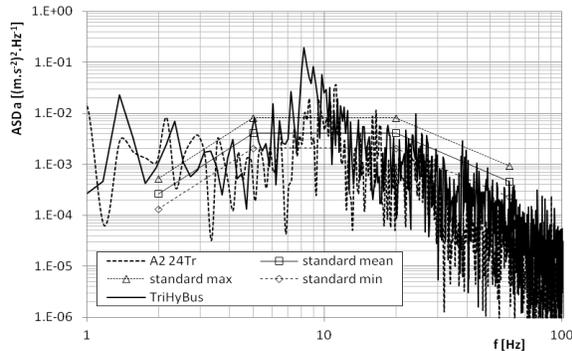


Fig. 7. Spectral density of transverse acceleration measured on vehicle roof, and comparison with data for a conventional vehicle.

## V. CONCLUSION

This paper was intended to demonstrate a vehicle operation monitoring concept of a different kind than the ordinary approaches which are based on vehicle stress measurement, stability monitoring and passenger loading. The motivation was to verify the ability of the present structure to sustain increased loads imposed by the hydrogen propulsion components. This configuration has been used in service for several years during which no negative effects on the structure were found. Long-term monitoring of random operating loads in vehicles enables fatigue damage for the locations of

interest to be evaluated on-line. It also provides source data for designing and implementing laboratory fatigue tests of components and structural details. Tests developed on this basis can reproduce in-service loads more faithfully even in the laboratory environment. A variety of techniques are available for this purpose. Random loading can be transformed to equivalent harmonic cycles or blocks of harmonic cycles. Laboratory fatigue tests can be made more severe and faster by shortening their duration, e.g. by omitting low severity cycles.

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