Operation Reliability and Diagnostics of Mechanical Systems via RDIS Application

Jiří Stodola & Petr Stodola
University of Defense Brno

OUTLINE

- 1. INTRODUCTION - RDIS
- 2. FAILURE RELATIONSHIP ANALYSIS
- 3. APPLICATION OF MONITORING OPERATION INFORMATION ON FAILURE RATE WITH THE USE OF CORRELATION AND REGRESSION ANALYSIS
- 4. CONCLUSION

1. INTRODUCTION - RDIS

Information system should contain, for example, the information as follows:

- boundary requirements for a system and its elements,
- list of potential failures, their basic discriminating features, their classification (negligible, marginal, critical, catastrophic),
- criteria for classification of failures (time flow, scope, conditions for their creation, occurrence in time, mutual relationship, external indications, causes, mechanisms, remedy complexity, etc.),

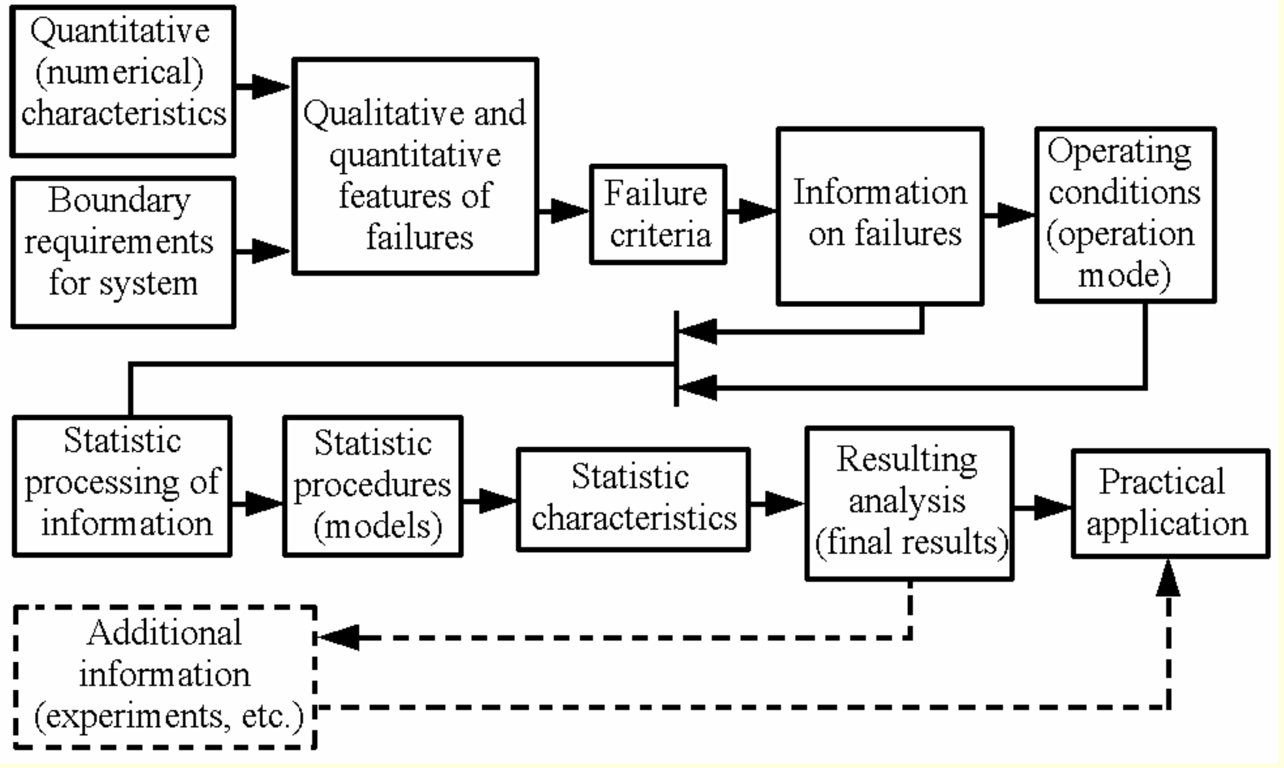
1. INTRODUCTION - RDIS

- diagnostic parameters, physical methods of diagnostics used, methods, methodologies, sensors, diagnostic signals, etc.,
- determination and characteristics of operating mode (continuous, cyclic, operating, general),
- technique of failure data collection in time (time protocol, formalized documents, automatic data collection, coding, classification, filtering, security, etc.),

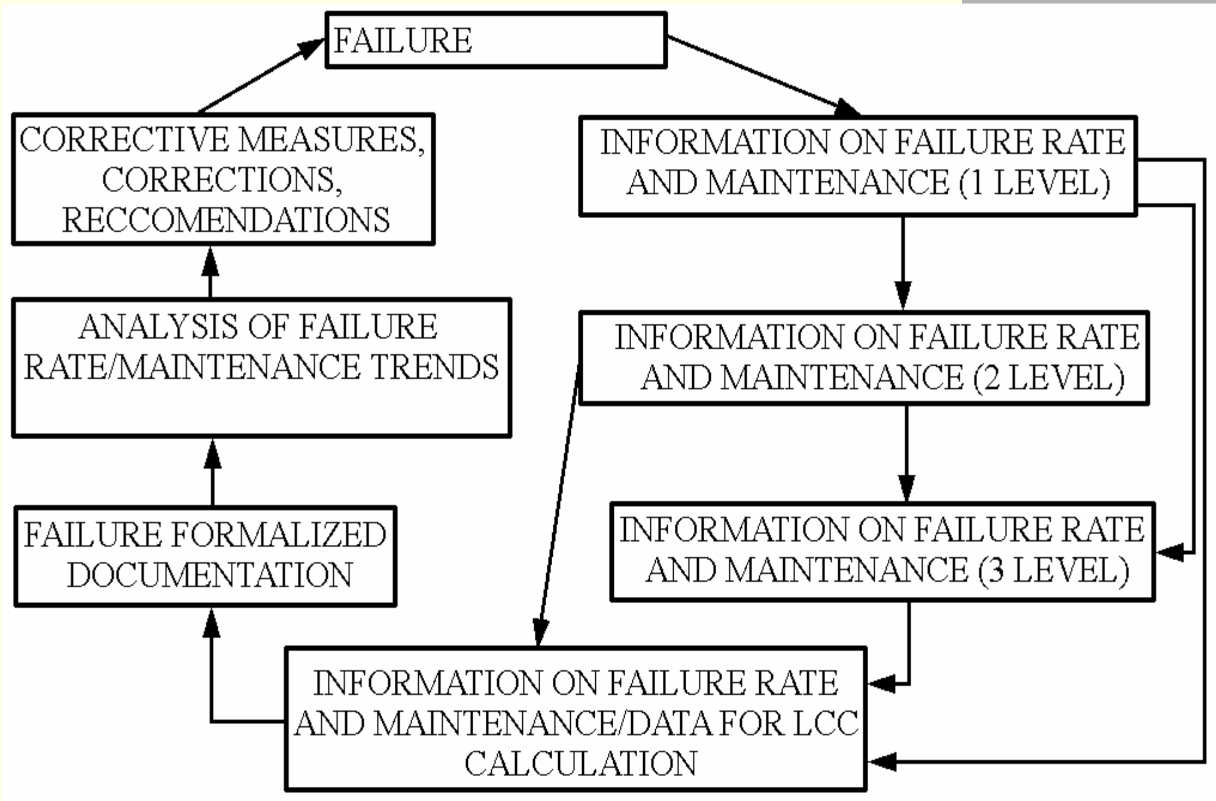
1. INTRODUCTION - RDIS

- methodology and analysis of information obtained (software, routine and special outputs, etc.),
- additional information or necessary experiments to explain complex outputs,
- elasticity, effectiveness, integrity, efficiency, compatibility (Microsoft Office, etc.), reliability (ISO 9001), periodical updating, open (modular) design, superstructure availability, departmental solution, etc.

RDIS block diagram



Block diagram of information about failure rate and corrective measures



2. FAILURE RELATIONSHIP ANALYSIS

- **Input information for the analysis of mechanical systems reliability can be presented as a set of vectors: v_i, $n_v(T)$, $t_{vi}(T)$ and r_{vi}, for which it is valid**
- $v_i = [v_1, v_2, ,\ldots v_i,\ldots, v_k]$, **(1)**
- $n_v(T) = [n_{v1}, n_{v2},\ldots,n_{vi},\ldots,n_{vk}]$, **(2)**
- $t_{vi}(T) = [t_{vi}(1), t_{vi}(2),..,t_{vi}(i),..,t_{vi}(k)]$ **(3)**
- $r_{vi} = [r_{v1}, r_{v2},\ldots,r_{vi},\ldots,r_{vk}]$, **(4)**

2. FAILURE RELATIONSHIP ANALYSIS

There are many methodologies and assessment to analyze data on mechanical systems, for example:

- Wöhler or Weibull fatigue tests,
- Simultaneous fatigue tests,
- Censured fatigue tests according to time or samples,
- Probability models,
- Approximative models,
- Correlation analysis,
- Testing procedures, etc.

2. FAILURE RELATIONSHIP ANALYSIS

- **An appropriate method is a correlation analysis related to the vector *$n_v(T)$;***

$$\left[n(v_i,v_j)\right]=\begin{vmatrix} n_{11} & n_{12} & \dots & n_{1j} & \dots & n_{1k} \\ n_{21} & n_{22} & \dots & n_{2j} & \dots & n_{2k} \\ . & . & \dots & . & \dots & . \\ n_{i1} & n_{i2} & \dots & n_{ij} & \dots & n_{ik} \\ . & . & \dots & . & \dots & . \\ n_{k1} & n_{k2} & \dots & n_{kj} & \dots & n_{kk} \end{vmatrix}$$

2. FAILURE RELATIONSHIP ANALYSIS

- **Where diagonal elements n_{ii} for i = 1, 2, …, k, determine the rate of independently occurring failures, and present simultaneously generated failures. It is valid failure rate, type v_i for i = 1, 2, …, k,**

$$\sum_{j=1}^{k} n_{ij} = n_{vi} = n_i$$

2. FAILURE RELATIONSHIP ANALYSIS

- **It is valid failure rate, type v_j for j = 1, 2, …, k,**

$$\sum_{i=1}^{k} n_{ij} = n_{vj} = n_j$$

2. FAILURE RELATIONSHIP ANALYSIS

- **It is valid number of all failures, type v_i and $v_i \cap v_j$, for i, j = 1, 2, …, k, within the interval $\langle 0, T \rangle$;**

$$\sum_{i=1}^{k} \sum_{j=1}^{k} n_{ij} = n(T)$$

- **$n_{ij} = n(v_i, v_j)$… failure rate, type v_i and v_j produced simultaneously,**

2. FAILURE RELATIONSHIP ANALYSIS

- **The matrix of relative failure rates is defined**

$$\left[p(v_i, v_j)\right] = \begin{vmatrix} p_1(1) & p_2(1) & \dots & p_j(1) & \dots & p_k(1) \\ p_1(2) & P_2(2) & \dots & p_j(2) & \dots & p_k(2) \\ . & . & \dots & . & \dots & . \\ p_1(i) & p_2(i) & \dots & p_j(i) & \dots & p_k(i) \\ . & . & \dots & . & \dots & . \\ p_1(k) & p_2(k) & \dots & p_j(k) & \dots & p_k(k) \end{vmatrix}$$

2. FAILURE RELATIONSHIP ANALYSIS

- **Thus, it will hold**

$$\sum_{j=1}^{k} p_j(i) = \sum_{i=1}^{k} p_j(i) = 1$$

- **where $p_j(i)$ … probability of simultaneous failures v_i and v_j.**

2. FAILURE RELATIONSHIP ANALYSIS

- **If $n_1, n_2, \ldots, n_k$ are non-negative integer numbers and if it holds that, then we shall expect $n_1, n_2, \ldots, n_k$ in multinonic distribution with a probability**

$$P(n_1, n_2, \ldots, n_k) = \frac{n!}{n_1! n_2! \ldots n_k!} \pi_1^{n_1} \pi_2^{n_2} \ldots \pi_k^{n_k}$$

2. FAILURE RELATIONSHIP ANALYSIS

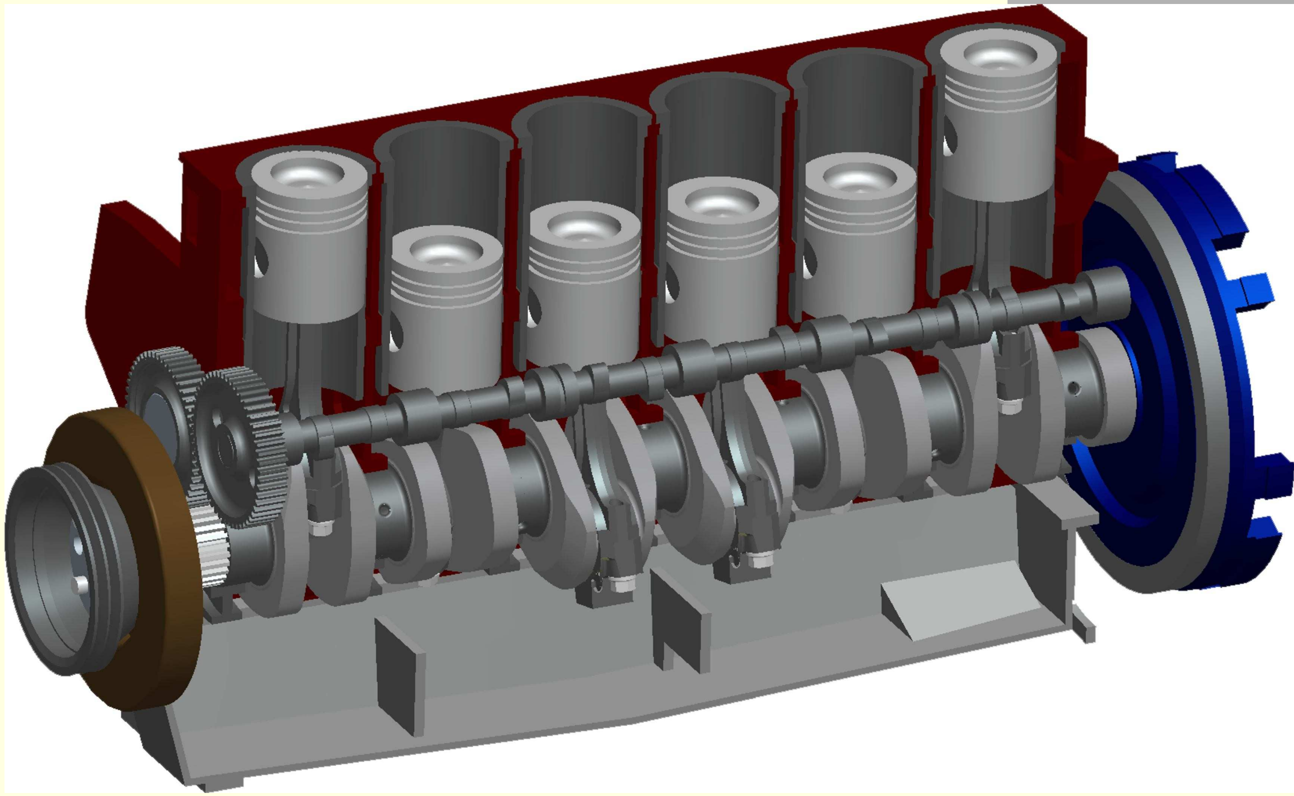
- **The distribution function of multinonic distribution of simultaneous occurrence of various types of failures provides to calculate strength of a possible stochastic dependence between them – the correlation coefficient**

$$r_{ij} = -\sqrt{\frac{p_i(i).p_j(i)}{[1-p_i(i)][1-p_j(i)]}}$$

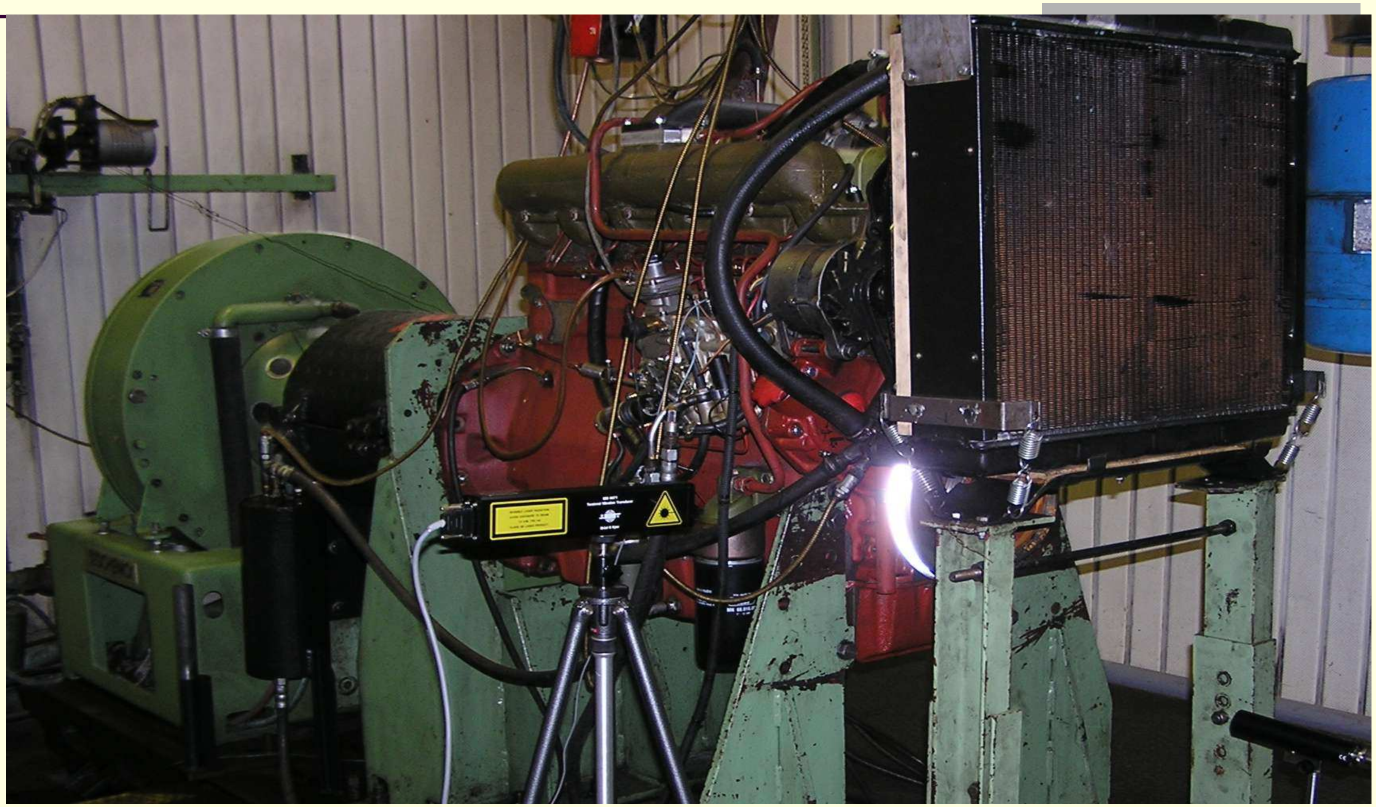
3. APPLICATION

RDIS included a study of operation failures of connecting-rod sliding bearings of the internal combustion engines.

3. APPLICATION



3. APPLICATION



3. APPLICATION

It referred to 7 connecting-rod sliding bearings, the failures of which were caused by the following 11 wear mechanisms. These are:

3. APPLICATION

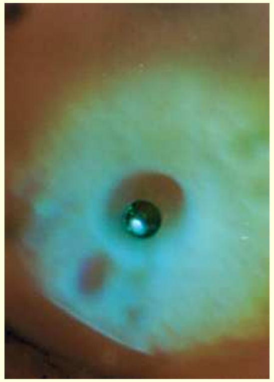
- **Adhesion, vector – v_1 ,**
- **Abrasion (knurling, cutting), vector – v_2 ,**
- **Erosion, vector – v_3 ,**
- **Fatigue, vector – v_4 ,**
- **Vibrations, vector – v_5 ,**
- **Cavitation, vector – v_6 ,**
- **Mixture, vector – v_7,**

3. APPLICATION

- **Peeling off the surface, vector – v_8 ,**
- **Corrosion, vector – v_9 ,**
- **Mechanisms of failures caused by changes of geometric shape (ovality, conicity, etc.), vector – v_{10} ,**
- **Mechanisms of failures caused by operating (technological or installation), vector – v_{11} .**

Products of wear process

◄ Abrasion particles

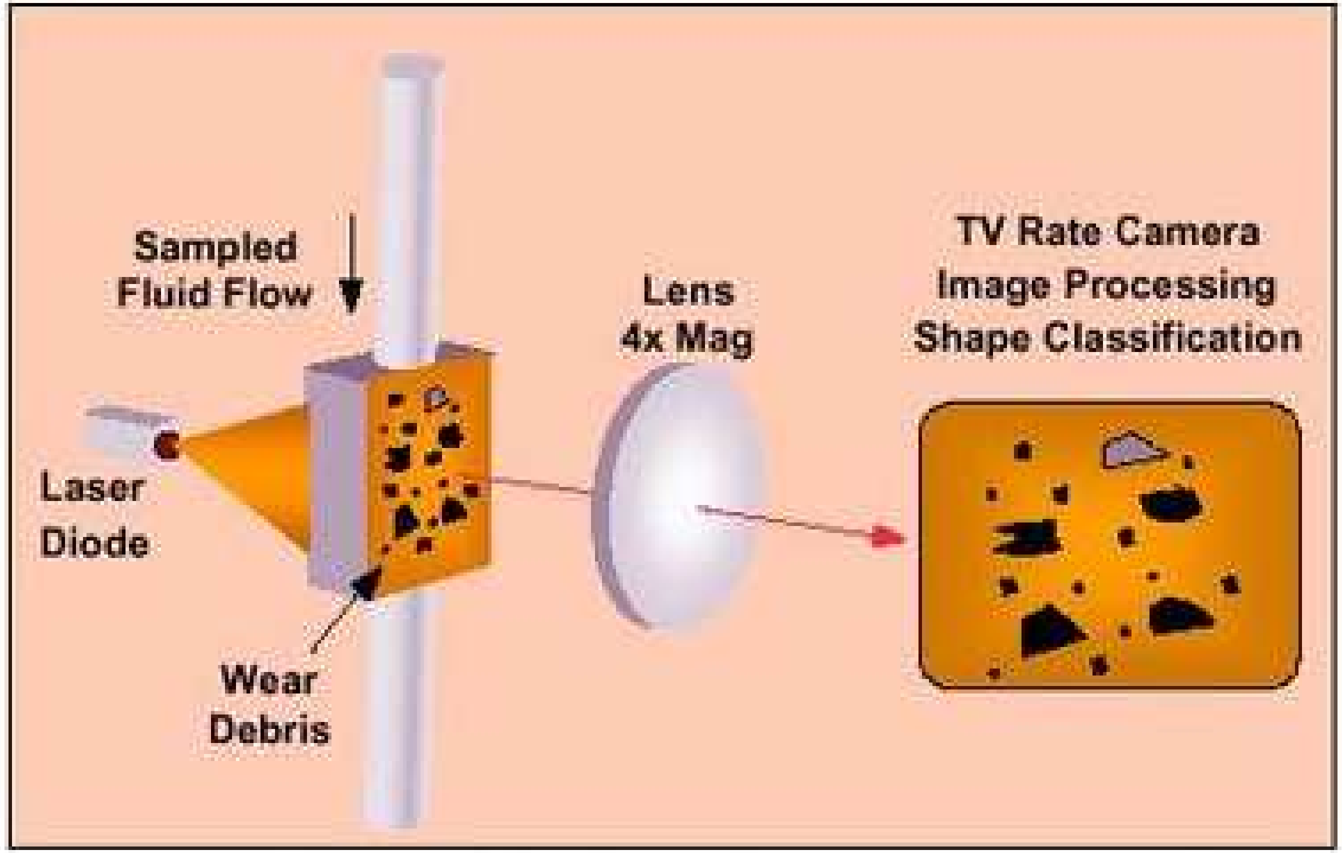


◄ Sferoids

▼ Syntetic fibres

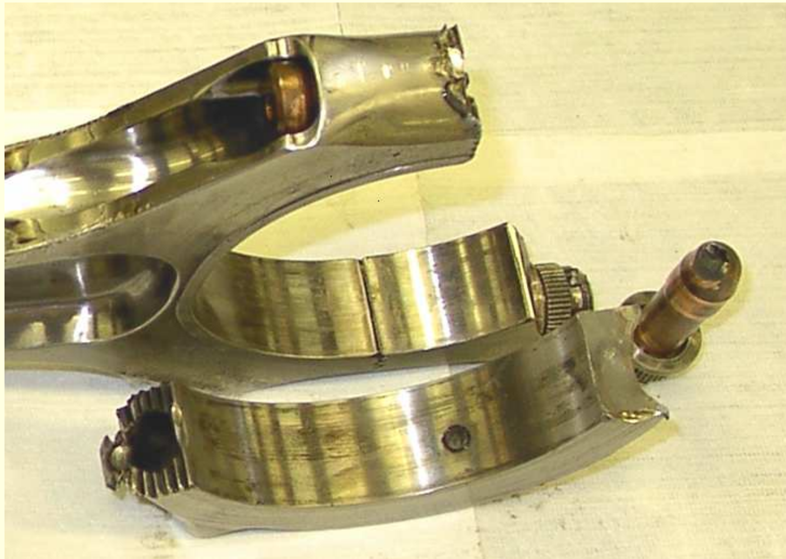
▼ Fatigue particles

Laser-Net Fines

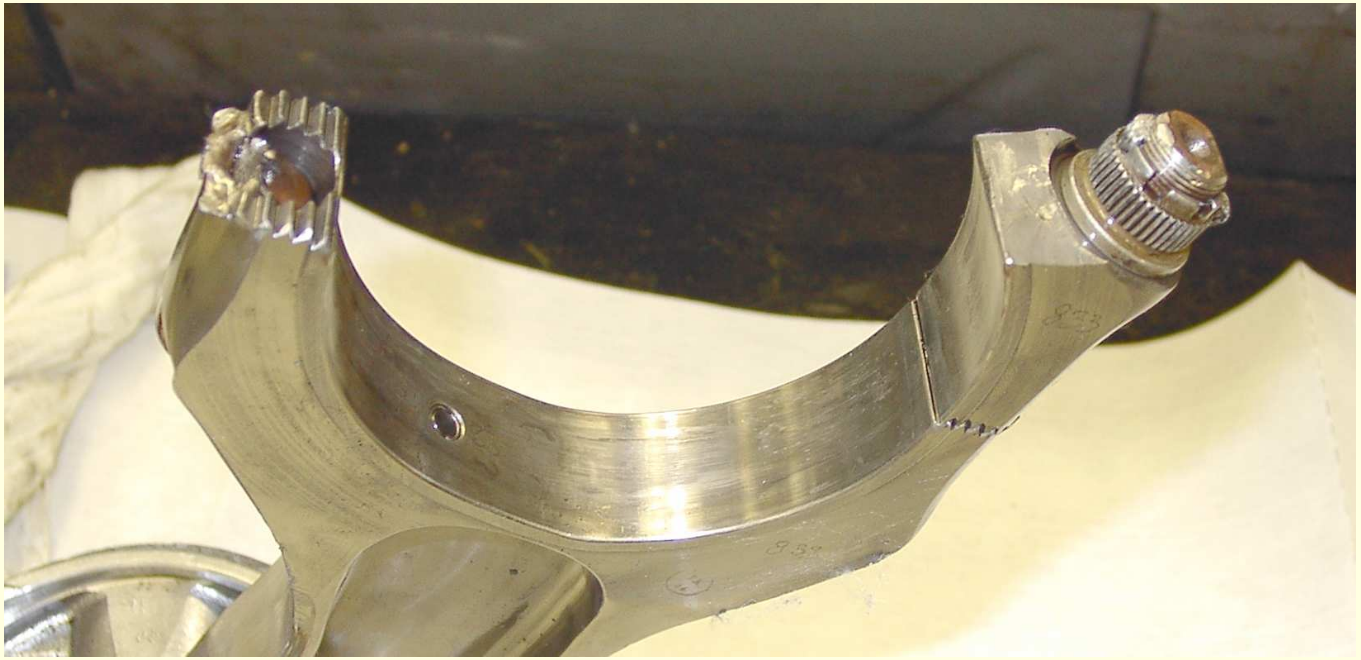


3. APPLICATION

- **Connecting rod**



3. APPLICATION - connecting rod



3. APPLICATION- crankcase

3. APPLICATION

- Piston, piston pin, piston ring, connecting rod

3. APPLICATION - connecting rod screw

3. APPLICATION

- For all mentioned mechanisms, typical characteristics (number, shape and size of wear particles, morphology of wear particle surface and worn bearing, etc.) were determined; standards, gauges and decision criteria for assessment of a technical condition in dependence on performance parameter (number of kilometers covered, number of hours worked Mh, fuel consumed, physical age, etc.) were stated.

3. APPLICATION

- The result of study was to approximately assess a residual life and prevailing mechanism of wear, vector – v_i for i = 1, 2,…, 11. Further solution consisted in identification of 35 basic features $(Z_1 – Z_{35})$, obtained by diagnostics of engines in view, specification of which can be seen in Tab. 1.

3. APPLICATION

- **Simple correlation analysis of featured pairs resulted in the matrix correlation coefficients in the form**

$$\left[r(Z_i, Z_j)\right] = \begin{vmatrix} 1 & r_{12} & \dots & r_{1j} & \dots & r_{1,35} \\ r_{21} & 1 & \dots & r_{2j} & \dots & r_{2,35} \\ . & . & \dots & . & \dots & . \\ r_{i1} & r_{i,2} & \dots & r_{ij} & \dots & r_{i,35} \\ . & . & \dots & . & \dots & . \\ r_{35,1} & r_{35,2} & \dots & r_{35,j} & \dots & 1 \end{vmatrix}$$

3. APPLICATION

- Correlation coefficient r_{ij} can be written

$$r_{ij} = \frac{\sum (Z_{ij} - \overline{Z_i})(Z_{ij} - \overline{Z_j})}{(\nu = 1) s_{zi} s_{zj}}$$

for $\upsilon = 2(N_{lab} + N_{oper})$ and with an estimate of coefficient of determination $d_{ij} = 100\, r_{ij}^2$

Tab. 2

4. CONCLUSION

- **For an actual given example, cases were analyzed when a time of operation (feature Z_3) is significantly stochastically dependent on further features Z_i. In practice, it was the analysis of features (Z_3 , Z_i) for i = 7, 8, 10, 23, at which an important correlation dependency was observed, in the following order**
- $\{Z_3 \leftrightarrow Z_8\}$ … $r_{3,8} = 0.84$; $d_{3,8} = 71\ \%$
- $\{Z_3 \leftrightarrow Z_7\}$ … $r_{3,7} = 0.70$; $d_{3,7} = 50\ \%$
- $\{Z_3 \leftrightarrow Z_{23}\}$ … $r_{3,23} = 0.68$; $d_{3,23} = 46\ \%$
- $\{Z_3 \leftrightarrow Z_{10}\}$ … $r_{3,10} = 0.62$; $d_{3,10} = 38\ \%$

4. CONCLUSION

- **These will be the following close relations:**
- **Time of operation – smooth wear of the center of sliding surfaces,**
- **Time of operation – smooth wear of the edges of sliding surfaces,**
- **Time of operation – friction corrosion of external surfaces,**
- **Time of operation – stains on sliding surfaces;**

4. CONCLUSION

- **The result of research provides important information enabling optimizing the operating diagnostics of objects tested (internal combustion engines) based on five important diagnostic parameters.**

Questions ?