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ON THE METHODS TO MEASURE THE REAL LOADING AT MECHANICAL SYSTEMS

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ABSTRACT. *The consideration of an accurate model of the real loading in the load capacity and reliability calculation bring numerous advantages (Dobre, Mirica, Cananau, 2010). If the real loading model is not available (the case of numerous concrete mechanical systems), this must be established using experimental data. The measurement and interpretation of the measurement results represent today an important subject in the conditions of existing possible modern instrumentations to develop these measurements. But the literature does not gives very explicit methodologies and development of measurement procedures and the interpretation of the obtained data using this modern instrumentation. The present paper has the aim to emphasize considerations on the measurement of the real loading to interpret the results and to propose a methodology for simultaneously measurement the real modulated and non-modulated loading and an adequate measuring chain. This methodology refers also to the principles of data storage an adequate form for interpretation of the real loading measurement in situ in order to extract the loading spectra and sequences as types of real loading models and finally to determine a better description of the real loading effects in load capacity and reliability calculation. An adequate measuring chain is presented. The paper continues previous researches of authors presented in different conferences or journals papers.*

KEYWORDS. *Real loading. Measurement. Mechanical systems. Reliability.*

1. INTRODUCTION

An important aim of research in mechanical engineering area is the inclusion of the aleatory real loading in the strength and reliability estimation. The real loading is in fact outside acting forces and torques - neglecting other influences - from system or its components; this type of loading is met in numerous application cases, for example: aviation, automotive, drilling platforms, wind turbines, reversible acting systems for mills etc. (see, for example, Buxbaum et all. 1992). The advantages of the taking into account the real loading regards (Dobre, Mirica, Cananau, 2010): 1. a more accurate strength calculation at fatigue of components; 2. the assessment of service life and reliability of these components; 3. the reduction of dimensions and weight of the components determined by the more accurate strength calculus; 4. a lower energy consumed by components' operation.

The consideration of the real loading in these actions could be realized using experimental data if loading models for the specified system or component are not available. The measurement is possible today using advanced possible technical instrumentation. But the literature does not present very detailed methods on developing the real loading measurement process using this modern instrumentation.

The aim of the present paper is to emphasize considerations about the measurement of the real loading with the present instrumentation (acquisition data card, processor, memory, software, etc.). Then a methodology for simultaneously measurement the real modulated and non-modulated loading is proposed, referring also to the principles of processing and interpretation of the obtained results in the scope to achieve the real loading model (loading spectra and sequences) determining a better description of the real loading effects in load capacity and reliability calculation. A classification of the real load of the mechanical systems followed by the presentation and characterization of the two main categories in which the various types of loading are, namely: modulated and non-modulated is approached in this paper.

The acquired data obtained using the proposed methodology can be processed later by different counting methods (classical and modern); this data could be filled with supplementary data so that the obtained loading model could describe as well as possible the extrapolated load to the entire service life of the components of the considered mechanical system.

A measuring chain adequate to the proposed measuring real loading methodology is proposed.

The paper brings as new aspects: an amelioration of the measurement methodology in accordance with the present capability of the hardware had at disposition; a proposed adequate hardware structure/chain achieved with components being of general use and easily obtained.

The paper continues researches developed by the Romanian school in this area: Dobre (2006); Dobre et al. (2008 and 2010); Mirica et al. (2008 and 2009).

2. THE REAL LOADING

Load means all external influences which may damage the operation of a mechanical system or of its component together or individually, at single or repeated occurrence (Buxbaum, 1992). The following external influences could be considered: forces, torques, temperature, radiation, corrosive environments, etc.

The concept of loading is considered in relation to resistance issues often as external forces and torques producing local stress (strains and tensions). Other environmental factors from the ambient medium are generally ignored (like temperature, humidity, lubrication, roughness, vibrations, etc.). Sometimes these environmental influencing factors are taken into consideration either in the strength or reliability calculation or in experiments by providing conditions that more closely resemble the real some (for example, samples or specimen-samples immersed in a container having sea water, which are tested on fatigue testing machine).

There are some references mentioning different loading processes measured usually (Buxbaum, 1992; Haibach, 1989; etc.): forces acting on the wheel of a car when driving, torque at a mill, bending of automobile wheel axle, pressure of an oil pipeline, etc.

3. LOADING MODEL – BASIC COMPONENT OF SAFETY ASSESSMENT

The real loading model is an essential part of the process for estimating the safety of operation (fig. 1). The safety in operation is one of the most important requirements which must respond a mechanical system and in fact all its components. The safety in operation is quantified either trough the reliability or the safety factor. Sometimes such as bearings the rating life afferent to certain reliability is determined.

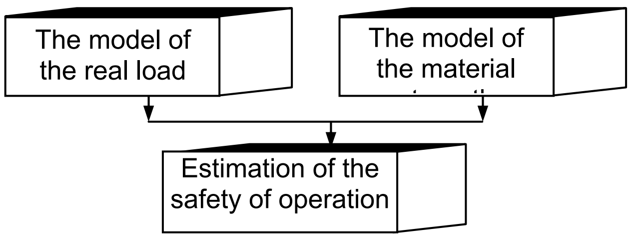

Fig. 1. Principle of assessment the safety of operation of a mechanical part

It is noteworthy that all procedures for estimating the safety in operation both on analytic and experimental way need a real loading model to characterize the load applied throughout the entire service life of the analyzed mechanical component and finally, of the mechanical system which it belongs to.

Thus, for a constructive (machine) element, over the loading applied to the entire system overlaps mainly the inner dynamic forces and torques. In case of gear transmissions these sinner loads are due to the gear teeth stiffness variation during operation (Niemann and Winter, 2002) and to other vibration processes with owner frequencies of the system. The model is an abstracting dedicated to simplify the real phenomenon so that it can be investigated with scientific and technical means at our disposal.

It should be noted that the loading model should characterize the operation of the entire analyzed mechanical system or a group of these systems (for example, all general assembly – tractors, automobiles, etc. – contain a group of mechanical systems). But it is possible that other dynamic processes influence a dynamic state characterized by an loading model; for example, the loading capacity of gears is characterized dynamically by two loading models: the application factor, K_A, and the dynamic factor, K_v.

The real loading is considered into the strength calculations by specific models. Following there are listed three very widely used theoretical models:

1. loading spectra;
2. loading sequences;
3. block programs.

The real loading supported by a mechanical system during a specified period of time is primarily characterized by the loading spectrum. This is defined as the all forces and torques applied during the period of time ordered by size and cumulated frequency (Dobre, 2006). The loading spectrum includes the following information regarding the real load supported by the system:

1. the total number of cycles;
2. the spectrum model from which shows the weight of different load level (value) of each load bin;
3. the maximum probable load level.

Although the loading spectra do not contain information on the sequence of counted cycles or on the load varying frequency (speed); these are currently the main way to characterize the real load due to the following advantages:

- there are easy to determine using data acquisition equipment for general use configured properly;
- loading spectra can be extrapolated to the entire service life of the studied system;
- loading spectra enable to implement the test of the operational stability performed on test rigs to other similar equipment.

Markov or Rainflow matrices are determined to take in to consideration the sequence of cycles with different amplitudes; it was found experimentally that the sequence of cycles influences the durability value. On this basis typical loading sequences can be determined; these loading sequences are sequences of quasi-aleatory cycles having the same probability of succeed as the real loading. A greater volume of experimental data than loading spectra has to be used to determine the Markov or Rainflow matrices.

The real loading model can be determined by performing experimental measurements (direct measurement) trough an operation simulation or a combined method.

4. SOME CHARACTERISTICS OF REAL LOADING

4.1. Classification criterions of loading processes

Two characterization of loading processes will be discussed detailed:

1. the classification criterion taking into account the variation over time and the mathematical description possibility of the loading processes (shown as names in the fig. 2);
2. the classification criterion based on the observation that the loading cycles are or not functionally conditioned (modulated and non-modulated loading).

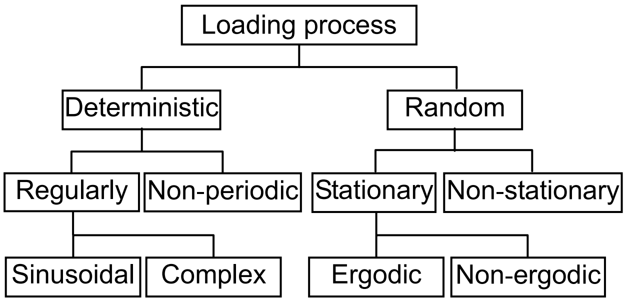

Fig. 2. Classification of the load processes about them variation over time and the mathematical description possibility (Buxbaum and Svenson, 1973)

4.2. Characteristic of real loading about them variation over time and mathematically description

Fig. 2 presents a classification of the loading processes which are subjected to the mechanical systems by the variation over time and the mathematical description possibility (Buxbaum and Svenson, 1973).

The loading processes are very rarely deterministic and can be described by univocal functions.

Generally, the operation of some mechanical systems (e.g. an automobile or a machine tool) contains phenomena, operations or processes showing an apparently random variation even they are repeated in identical conditions. In this case the loading processes are random and can not be described by explicit mathematical expressions, as for deterministic processes. The random loading processes can be continuous and discontinuous and can be produced by:

- changes of loading status;
- walking or flight maneuvers (change of the direction, speed, altitude);
- manufacturing processes;
- adjusting and control processes;
- air turbulence;
- rough road surfaces and road speed bumps;
- sea waves;
- vibrations of propulsion system;
- other vibratory excitations.

A very important characteristic of the stationary loading processes is that they enable a deterministic model of the real loading (loading spectra) or quasi-deterministic (loading sequences based on Markov or Rainflow matrices).

A random loading process is stationary if its mean and the moment of second order are not sensitive to a second order temporal translation, τ. To check its stationarity, loading process measurements are performed on a sufficient long duration and the stationarity is tested trough the testing the ergodic character of the recorded signal. For this purpose, for different loading records represented, as example, by the torque T(t), the mean size

$$m = \frac{1}{\Delta t} \cdot \int_0^t T(t) \cdot dt \qquad (1)$$

and the temporal autocorrelation function:

$$\tilde{R}(\tau) = \frac{1}{\Delta t} \cdot \int_0^t T(t) \cdot T(t+\tau) \cdot dt \qquad (2)$$

are calculated. If the results given by expressions (1) and (2) are invariant, then the loading process is stationary and the recording duration is sufficient to be achieved a loading model.

4.3. Modulated loading

Due to the operation (Gnilke, 1980) there are two loading situation: 1. the shafts usually support a symmetrical alternating bending stress and pulsed torsion; 2. the rotating bearings are loaded with forces having constant direction and orientation; 3. the teeth of gears are pulsed stressed.

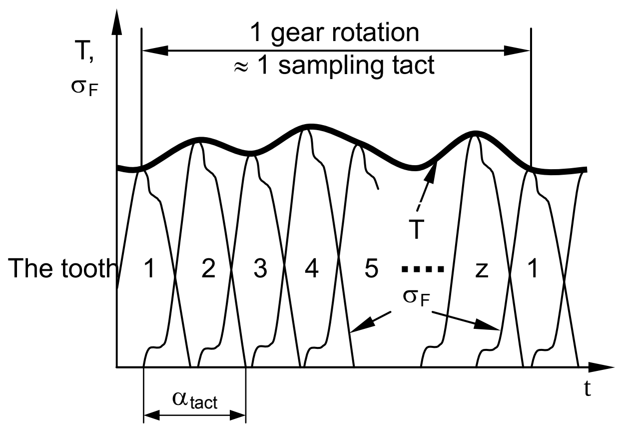

Fig. 3. Modulation of tooth root stress caused by the gear torque (about Seifried, 1973)
T – torque at pinion; σ_F - maximum tooth root stress at pinion; α_{tact} – time between the mesh entry and output.

Further, some aspects regarding stress of gears are presented; the phenomenology could be extended to shafts and bearings. The tooth root stress usually varies between 0, when the tooth is not in mesh, and a maximum value dependent on the instantaneous torque which occurs during tooth mesh (fig. 3). Therefore, the tooth root stress is always pulsating modulated; also the tooth loading is modulated.

In the case of the random loading processes, all the gear teeth carry over the time (long enough) as frequently all torque variations. Then this torque acts as a modulation function on pulsed stress on the tooth root stress. It is noted that the number of teeth loading cycles is functional conditioned and univocal. From the point of view of some tooth it doesn't matter the speed of gear, but the instantaneous torque when the tooth is in mesh. On this finding is based the exceedance time counting method. It involves measuring (and recording) of the values of the loading with a synchronized tact depending on the rotation angle. The modulated loading measuring principle is shown for the auto gearbox example (fig. 4); measured using strain gauges, the sampling being performed in conjunction with entry shaft rotation; the rotation of output shaft is measured to detect the gearbox step. The registration can be done without difficulty numerically on a laptop or other digital storage device.

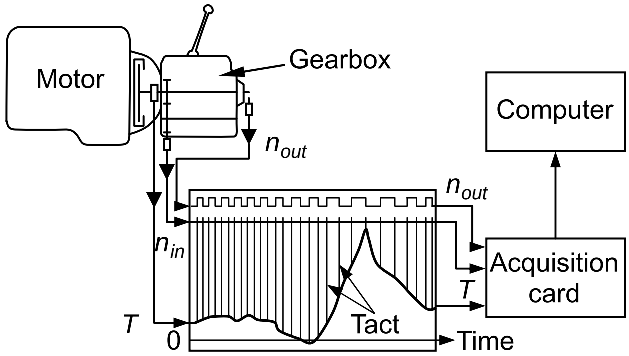

Fig. 4. The principle of measuring the real load applied to a car gearbox (about Seifried, 1973)

T- torque of entry shaft in gearbox; n_{in} –rotational speed at gearbox entry; n_{out} –rotational speed at gearbox output.

As in the case of shafts which are bending stressed, the rotation frequency of gears is generally higher than the frequency of external loading variation. Each tooth supports all the phases of the external loading function with the same frequency over time and receives the maximum loading at its frequency. Some deviations from this rule appear only in very rare cases, when the torque has more variation cycles between the input and output of tooth mesh; an example is the gear drive system of a solar panel effecting very slow movements while the wind acts on it with a much higher frequency than the one of mesh.

With very rare exceptions, such as the case of planetary transmissions, the loading experimental study of gear transmissions requires the use of strain gauges attached on the shaft. The useful signal of the strain gauges mounted in Wheatstone bridge is transmitted using a telemetry system from an emitter fixed on rotating shaft to a receiver (processing stationary part).

The telemetry transmission systems facilitate the transmission of signals from almost any distance between the measured rotating shaft and the recovery electronic equipment. The conventional telemetry systems work with a voltage powered oscillator mounted on the rotating shaft (emitter) which emits a frequency spectrum (in FM frequency band) dependent of the measured torque. Then the spectrum is demodulated and converted by receiver to a DC signal proportional to the original measured torque.

Fig. 5 presents schematically telemetric monitoring equipment. The output signal type is of unitary type compatible with the computer acquisition data card. It is preferred a laptop equipped with a PCMCIA card because it is easy to handle and has high storage capacity without the risk of disruption or distortion of the signal because it is numerically stored.

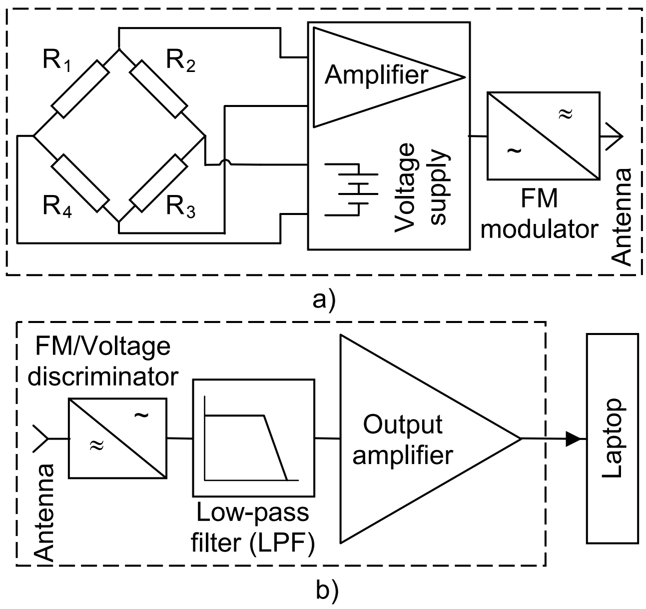

Fig. 5. Structure of a telemetry system: a) mobile equipment mounted on the moving machine parts (e.g. shafts), b) stationary equipment connected to the computer (laptop)

4.4. Non-modulated loading

The non-modulated loading has the variation cycles not univocally determined. The constructive elements with non-modulated loadings are generally housings and various mechanical structures (frames) such as bridges, crane bodies, etc. In this case, the establishment of the variation loading cycles used in methods of statistical processing is a very important issue in the approach of the loading model.

The registration of non-modulate loadings is made with sampling clock generated at equal time intervals.

There are rare exceptions of functionally modulated loaded housings and structures. The structure of a very shallow boring well which carried over during its operation time is such example; it has modulated loading and its cycles are the performed drillings.

5. ISSUES OF LOADING MEASURING AND MODELING

To achieve adequate load models based on experimental data it is necessary that measurement and their processed results to take into consideration the issues listed briefly below:

1. the model should characterize the loading for the entire service life of the analyzed mechanical system;
2. the measuring period of time is severely limited due to the related expenses including also the losses due to disruption of normal operating processes for installation and removal of measuring systems;
3. the necessity to ensure a long enough period of recording time;
4. the necessity to extrapolate the result (model) to the entire service life of the analyzed system;
5. the study of the loading process has to be done taking into account the basic functional features of the mechanical system components as: shafts, bearings and gears on the one hand and housing and other structures on the other hand. It has to take into account the exceptions, too (e.g. non-modulate loaded gear wheels or modulate loaded structures);
6. the necessity to achieve simultaneously measured data for the same both existing models: modulated (for some components of the system) and non-modulated loading (for the other part of components);
7. some components in rotation motions (mainly those with modulated loading) hamper the process of data transmitting to the recording system;
8. statistical data processing methods are improvable and it is useful that measured data to be stored in the as little processed form and in a sufficient volume (permitted by the current memories) so that those could be processed by the possible new methods;
9. as it was indicated, the loading model must characterize only the external influences of the analyzed mechanical system and thus the vibration effects of the additional internal causes to be removed by filtering the system recorded signal.

The loading history is naturally affected by currently distortions occurring in the measuring chain (system vibration, measuring system noise). The classical methodology used appropriate low-pass filters with cut-off frequency to effectively separate the loading history by the high frequency disturbing signals. For example, in the case of a tractor transmission the frequency analysis of the loading history measured on a shaft shows basic vibrations in the lower frequencies range produced by the dynamic variations of the wheel loading (as a result of the ground bumps) and by the oscillating system in which is part the driving shaft. These vibrations are superimposed by the wheel vibrations due to the pneumatic tires and also by high frequency vibrations produced by the engine that cross almost undamped the gearbox. Over these vibrations of interest there are overlapped high frequency vibrations that can be eliminated by an appropriate filtering. Aspects on measured signal filtration procedures are detailed for example by Buxbaum (1992).

Taking into account the presented issues (but also other aspects not mentioned in this paper) a measuring methodology and an appropriate measuring chain have been proposed by authors.

6. BASIC PRINCIPLES OF THE PROPOSED LOADING MEASURING METHODOLOGY

Basic principles of the proposed methodology for the loading measuring are listed below

1. The operation principles of the analyzed mechanical system are studied and the measuring points of the loading using the strain gauges are established.
2. Measurements of the following sizes are effected simultaneously:
   a) the torque on one or more system shafts chosen adequately to determine the modulated loading of all components having the same type of loading;
   b) the stress on enough number of structure points chosen adequately to determine the stress at any point of the structure;
   c) the rotating movement of the shaft, which torque is measured for, by issuing a synchronous sampling tact with predetermined step angle of its rotation;
   d) if it is necessary, other specific signals are recorded, e.g. for auto gear boxes there have to be established the speed steps which the measured results are corresponding to.
3. There is made the measurement chain calibration in order to record the load values themselves.
4. There are made vibration measurements in order to be able to filter the measured signal to eliminate the influences of internal vibration processes of the studied system.
5. The measured values are placed in classes and there are recorded integer numbers corresponding to those classes. The number of classes which make up the range of loading value variation should be large enough not to affect the measurement accuracy, but the files must contain integers and has to be text type to be able to store large volumes of results without special conditions.

7. A PROPOSED CHAIN TO MEASURE REAL LOADINGS

The considered measuring chain is made using general components: the acquisition card, processor, memory, software, etc. These components have high performance technical characteristics particularly in terms of proposed measuring methodology requirements.

Fig. 6 presents the configuration of a measurement chain enabling the measurement and simultaneous recording of data for non-modulated and modulated loadings. The data are stored in files created automatically at different addresses for data of non-modulated and modulated loadings. The text files enable high volume data storage and their easier processing in the later research stages. For the non-modulated loadings the recording is done with the frequency counter time of the data acquisition card set before the recording start.

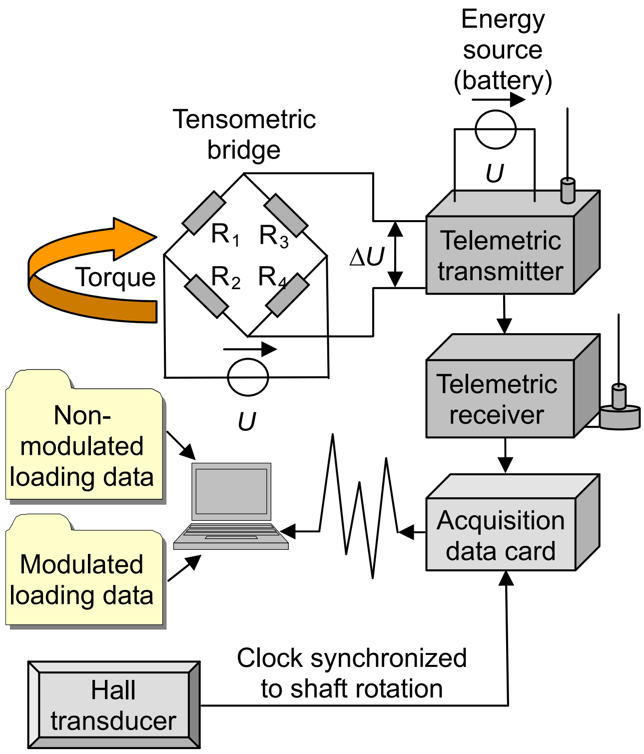

Fig. 6. Modern telemetric measuring system of real loading (simultaneous measurement of modulated and non-modulated stress)

U – tension; ΔU – tension variation proportional to measured loading; $R_1 ... R_4$ – strain gauges of tensometric bridge.

For modulated loading data measuring, the acquisition card receives the signal from the Hall transducer for each clock synchronized to the rotation of a shaft, or to mesh of the same tooth of the analyzed gear. The registered instantaneous loading value of data corresponding to every signal given by the Hall transducer is stored simultaneously both in the current file for non-modulated and modulated loading. So, a database that follows to be to be further processed is obtained.

In the proposed measurement chain the signal is stored unfiltered; the signal filtering will be done later on the basis of owner system frequencies experimentally determined.

8. CONCLUSIONS

The following conclusions are pointed out below.

1. The mechanical systems are made from components subjected to complex real loadings.
2. A classification of the loading processes shows their types about two different criteria: the variation over time and the mathematical description possibility of the loading processes; the loading cycles being or not functionally conditioned.
3. A proposal to ameliorate the classical real loading measuring methodology according to increased performances of actual measuring chain components is discussed.
4. The proposed simultaneous measurement of real modulated and non-modulated loading allows a better description of their damaging effects and a more accurate assessment of the deterioration level for the analyzed system components.
5. The proposed measurement methodology requires providing a long enough recording time; also the recorded data volume must be large enough to be able to be properly extrapolated to the entire operation time.
6. The proposed measurement chain contains components of high performance of general use (high capacity storage, processors, memory and communication lines with very high frequencies, etc.) having a relatively lower cost price.
7. Data format and their organization must allow their easy access and high processing speed.

REFERENCES

BUXBAUM, O. et all. (1992). Bestriebsfestigkeit. Sichere und wirtschaftliche Bemessung schwingbeanspruchgefährdeter Bauteile, Verlag Stahleisen, Düsseldorf.

BUXBAUM, O., SVENSON, O. (1973). Zur Beschreibung von Betriebsbeanspruchungen mit Hilfe statistischer Kenngrößen, ATZ 75, Nr. 6, pp. 208-215.

DOBRE, G. (2006). Organe de maşini. Angrenaje. Transmisii cu roţi dinţate (Translated in English: Machine elements. Gears. Gear transmissions). Vol. III. 172 pages, BREN, Bucureşti, ISBN (16) 973-648-583-8, ISBN (19) 978-973-648-583-1.

DOBRE, G., MIRICĂ, R. F., CANANAU, S. (2010). On the Real Loading Modeling of the Mechanical Systems. Fiabilitate şi Durabilitate/Fiability and Durability, Nr. 1, pp. 1-6, Editura Academică Brâncuşi, Târgu Jiu, ISSN 1844-640X.

DOBRE, G., MIRICĂ, R.F., MILOIU, G., ITU, V., DUMITRESCU, I. (2008). On the Loading Modeling of the Mechanical Systems, The 13th International Conference on Machine Design and Production, 03 - 05 September 2008, Istanbul, Turkey, Volume II, pp. 417-480.

GNILKE, W. (1980). Lebensdauerberechnung der Maschinenelemente, VEB Deutcher VEB-Verlag Technik, Berlin,

HAIBACH, E. (1989). Betriebsfestigkeit: Verfahren und Daten zur Bauteilberechnung, VDI-Verlag, Düsseldorf.

MIRICA R.F., DOBRE G., ITU, V., DUMITRESCU, I., MILOIU, G. (2008). Aspects Regarding the Loading Modeling for Gear Transmissions, With Application in the Mining Industry, The 13th International Conference on Machine Design and Production, 03 - 05 September 2008, Istanbul, Turkey, Volume II, pp. 481-496.

MIRICĂ, R. F., DOBRE, G., ITU, V., DUMITRESCU, I. (2009). On the Theoretical-Experimental Modeling of Loading of the Mechanical Transmissions, Proceedings of 3rd International Conference on Power Transmissions, 1-2 October 2009, Kallithea – Chalkidiki, Greece, pp. 291-296, ISBN ISBN 978-960-242-662-2.

NIEMANN, G., WINTER, H. (2002). Maschinenelemente. Band 2: Getriebe allgemein, Zahnradgetriebe - Grundlagen, Stirnradgetriebe. Springer Verlag, Berlin, ISBN: 978-3-540-11149-8.

SEIFRIED, A., BUCK, G., MAIER, W. (1973). Statistische Fahrmechanik als Grundlage zur Berechnung von Fahrzeugantrieben, Automobiltechnische Zeitschrift, Nr. 5, pp. 163-169.

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