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PRACTICAL OVERVIEW OF TOOLS AND METHODS FOR RELIABILITY IMPROVEMENTS IN TRANSPORT INDUSTRY

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Abstract: *This paper presents a brief overview of tools and methods for improving both safety and reliability in all the transport sectors (as automotive, railway, aerospace); then proposes a new methodological approach for the modern research of quality by a stricter integration between theory and experiments applying it in practice on a mass oriented application.*
***Key words*:** *total quality management, accelerated life tests*

INTRODUCTION

Due to the rapid evolution and the high criticality of the modern transport market, even slight deviations in reliability targets or discontinuity in the production capability, can provoke very huge losses for every industrial enterprise. Even minor inobservances in design specifications or in manufacturing processes of the sub-components by suppliers can lead to severe effects to the final production inside the transport factory. Unforeseen maintenances and costs under warrantee can suddenly erode the slight mark-up (typically less than 20%), transforming a profitable business in a financial break-down.
Quick responding methods for predictions and well-defined problem-solving strategies are necessary to overcome these barriers. Experimental tests are a fundamental practice for improving reliability and functionality of mass-oriented products. But, since the high level of quality of modern commercial components (in the order of few PPMs of failures in each transport field), accelerated life tests have to be properly integrated by advanced tools for reliability deployment based on failure models and statistical evaluations. On one side, for example, Design of Experiments (DOE) can be used for planning the Accelerated Life Testing (ALT); Analysis of Variance (ANOVA) for reducing the variability of measurements; failure models for interpreting the physic of phenomena of damage. On the other side, Failure Reporting, Analysis, Corrective Action System (FRACAS) and Failure Mode and Effect Analysis (FMEA) are irreplaceable to highlight on which criticalities to focus the experimental research, Fault Tree Analysis (FTA) and Reliability Analysis of in-service failure Data (RDA) to foresee the theoretical and authentic behaviour of reliability. But only strictly joining the Design for Experiments techniques (DOE, ANOVA, etc.) to the Design for Quality methodologies (FRACAS, FTA, FMEA, RDA) is possible to manage an “integrated approach” of Total Quality (TQ) and to move the targets for Reliability, Availability and Maintenability (RAM) besides the current limits [10].

AN INTEGRATION OF METHODS AND TOOLS FOR RAM IMPROVEMENTS

Theoretical and experimental methods, made by standard and not standard procedures, were incorporated in an integrated and original approach with the aim to improve the existing know-how about reliability, safety and maintainability of mechatronic devices.

Figure 1. Dividing a complex system in basic parts

After dividing the complex system (fig. 1) in its basic parts and deploying a deep comprehension of relations between parts and system's functionalities, the integrated approach followed the steps of:

1. State-of-art: using specific datasheets and other information from the scientific literature a quick, but approximate evaluation of reliability was performed; starting from the estimated MTTF, by proper correcting parameters, a satisfactory value for failure rate can be obtained;
2. Suppliers' data: requiring additional reliability information to the suppliers about durability of specific parts or other critical aspects, a better accuracy in prediction can be obtained; this action plan permits transferring an unambiguous and detailed know-how from suppliers;
3. On-field data: acquiring information from customer service about criticalities, failures, maintenance tasks, guarantee costs, but also about use (e.g. mileage per year) and misuse a better comprehension of reliability behavior in like-real conditions is possible; by a relatively low amount of data (failure times), accurate models for reliability can be drawn;
4. Simulations: focusing on critical components or specific situations, FEM tools can be used to compare different physical aspects increasing the knowledge for design or process; critical interactions between components can be easily investigated;
5. Experiments: looking into precise samples and significant conditions of loads, either by standard testing machines or pioneering equipments, experimental evidences and confirmations can be obtained; accelerated tests also permit to predict far away failure conditions even for highly reliable systems;
6. Model developments: merging all the previous information models for damage predictions can be developed; since the resources needed, this deep and labored level of comprehension on reliability aspects is justified only for few and specific situations.

THE CASE STUDY OF THROTTLE BODY

Reliability improvements were focus on an innovative family of throttle bodies, already installed or next to be installed in millions of specimens on different car brands. In a fuel injection engine, the throttle body is the part of the air intake system that controls the amount of air flowing into the engine, in response to driver input. A throttle body is somewhat analogous to the carburettor in a non-injected engine.

The Throttle Body (fig. 2) is usually located between the air filter box and the intake manifold, and usually attached to, or near, the mass airflow sensor.

Figure 2. A throttle body (by Magneti Marelli)

The largest piece inside the throttle body is the throttle plate, which is a butterfly valve that regulates the airflow. On many cars, the accelerator pedal motion is communicated via the throttle cable, to activate the throttle linkages, which move the throttle plate. In cars with electronic throttle control (also known as "drive-by-wire"), an electric motor controls the throttle linkages and the accelerator pedal connects not to the throttle body, but to a sensor, which sends the pedal position to the Engine Control Unit (ECU). The ECU determines the throttle opening based on accelerator pedal position and inputs from other engine sensors.
When the driver presses on the accelerator pedal, the throttle plate rotates within the throttle body, opening the throttle passage to allow more air into the intake manifold. Usually an airflow sensor measures this change and communicates with the ECU. The ECU then increases the amount of fuel being sent to the fuel injectors in order to obtain the desired air-fuel ratio. Often a throttle position sensor (TPS) is connected to the shaft of the throttle plate to provide the ECU with information on whether the throttle is in the idle position, wide-open throttle (WOT) position, or somewhere in between these extremes.

AN INTEGRATION OF ANALYSIS

The throttle body has been progressively improved in reliability and safety, hitting the successful target of 20 PPM of fails at 1 year of use, by a full-scale RAM integrated study (still in progressing) on its criticalities, paying particular attention to use proper methods and tools for each specific aspect of weakness (fig. 3) as:

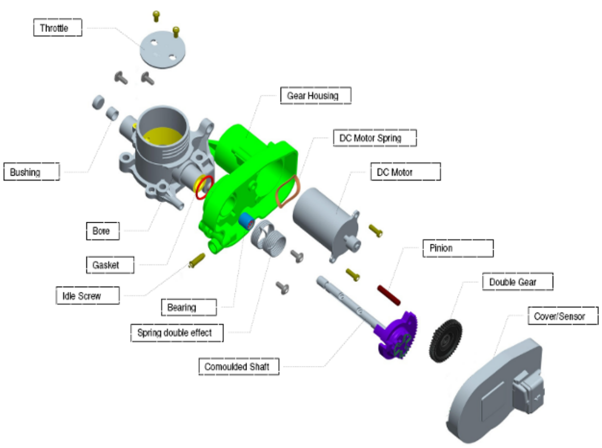

Figure 3. Exploded view of a throttle body

- ✓ Bushing : a Reliability Data Analysis (RDA) on in-field failures was performed with a Pareto comparison and ranking of the failure causes. Data were so numerous (around 300 failure times) permitting to distinguish 6 different failure causes, including a NTF (No-Trouble-Found) condition appearing with around 50% of share on data (fig. 4). Specific and no-elementary models for failure rate could be developed (also a complete "bathtub" model was distinguished) in a nonparametric analysis [4, 5]. According to this information, a subsequent redesign of functional solutions was performed and mainly aimed to increase the contact area between the wigging electrical contacts;

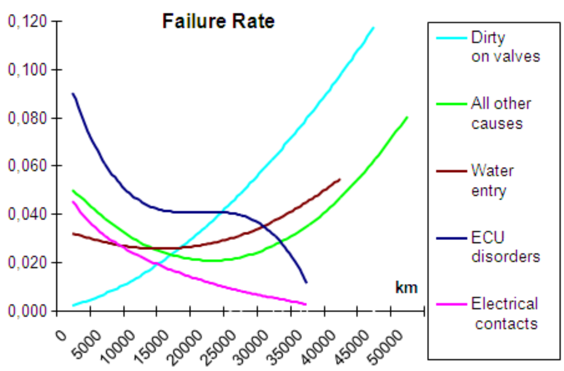

Fig. 4. Failure rates from in-field data

- ✓ Gear Housing & Cover : an elaborate process of Design of Experiments (DoE) regarding studies on chemical mixtures was performed (and is on-going) to select the proper composite materials for each specific application and working condition; starting from standards and datasheets, but also acquiring information from suppliers, specific experimental tests were planned and performed; appropriate methodological solutions were developed to reduce the need of time and resources and to interpret the high variance of data
- ✓ DC Motor : Accelerated Live Tests (ALT) were planned with a complete functional design of specific testing equipments able to perform a fatigue test on these electrical components under proper loading and environmental conditions; manufacturing of equipments and testing phases are going on.
- ✓ Double gear : a Design Review (DR) using stochastic FEM simulations was performed; by Statistical Process Control (SPC)

techniques it was possible to acquire draft geometric data regarding the most critical aspects of products/processes (for example, the respect of tolerances in the alignment between axis of plastic gears) defining the process capability; by stochastic FEM simulations (using Ansys WB FEM software coupled with KissSoft code for gear's profile design), modifications in geometry and axis position together with manufacturing advises were proposed to outguess blocks of gears;

- ✓ Spring Double Effect : a Design Review (DR) following standards for dimensioning was initially performed; then a static, dynamic, linear and non linear FEM simulations were used for a detailed evaluation of working conditions, stress-strains levels, critical zones, etc. A proper campaign of Accelerated Live Tests (ALT) were planned and realized designing and manufacturing of proper testing equipments for a fast application of fatigue loads.

In this article space is not provided for a detailed representation of each step of the integrated analysis limiting the description to two opposite RAM aspects:

1. a quick and easy estimation of reliability for the whole component using failure data provided by datasheets;
2. a accelerated life testing of resistance and endurance on a specific, elementary but critical part (the "double effect" springs).

RELIABILITY FROM DATASHEETS

The first step toward the complex RAM analysis was to obtain a quick but approximately prediction of reliability of the whole system (the "throttle body") acquiring failure data from "the state of art". Following information collected in specific manuals [1], that consists in failure rates coming from external experiments, the reliability of every single components (more than forty) and the reliability of whole assembly were calculated.

Spring (Summary)				0.6134			
				0.4171M			
Spring				0.1433			
				0.9772M			
	Mil		<	0.7614			
		AIF 13514-000	<	1.8146	0	0.5511	3-479
		DOR NPRD-111	<	6.0606	0	0.1650	3-479
		GM 18283-000	<	35.9118	0	0.0278	3-479
		NSB 18155-000	<	1.7562	0	0.5694	3-479
	Unk			1.5155			
				0.9772M			
		AIF 18459-000		21.8731	3	0.1372	3-479
		GB 27027-000		0.1050	-	--------	3-479
		GM 27030-000		0.9772M	61	62.4204M	3-479
Spring,Assembly	Unk	GM 27030-000		2.4351M	76	31.2102M	3-479
Spring,Brake	Unk	GM 27024-000		1.1364	1	0.8800	3-479
Spring,Compression	Unk	GF 18459-000		23.8453	4	0.1677	3-479

Fig. 5: Example of database for failure data

Although valid for a preliminary evaluation, these results, mainly related to literature data (fig. 5), are not suitable for an accurate demonstration of reliability since:

1. the failure data, available in the scientific literature, come from experiments realized (by others) in different conditions respect to the working conditions for our system (different components, environments, loads, etc.)

2. the reliability behaviour of the whole system is defined by the particular structure of functional connections between each component (Fault Tree Analysis) but these first evaluations are fundamental for the following steps

Against the first remark regarding the fact that reliability data from literature could be not representative of the reality of a specific system, both in standards and in industrial practice corrective factors are commonly used. Without entering in details, in this RAM analysis 6 different factors were applied (either according to standards or specifically developed) to take in count, for each part, of:

1. manufacturing quality
2. environmental conditions
3. level of technological development
4. effective work loads
5. level of complexity for the assembly

A Fault Tree Analysis (FTA) was used to set up the logical connection between parts and the way to impact of every possible fail (fig. 6).

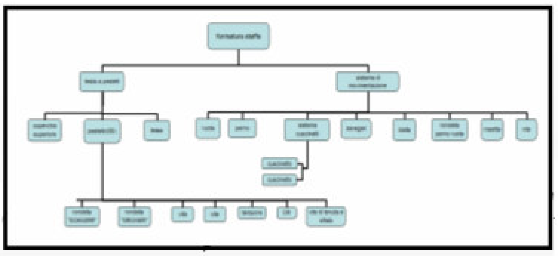

Fig. 6: Logic connection between components

With the aim to move the analysis toward a better precision of reliability, in the next step, the main RAM functions were recognized (and all the others, not fundamental for reliability or safety, neglected). Each main function was divided in different sub functions and addressed to each component creating a correlation matrix (fig. 7) that give several information as:

- which component participates to guarantee a specific functionality (and which not)
- (and dually) which function misses if a specific component fails.

Descrizione componente / interfacce	Quantità	Matricola MM	Progressivo	distribuire aria ai cilindri (sezione / geometria condotti e volume plenum) AA	convogliare acqua (sezione / posizione di passaggio circuito acqua) AB	requisiti acustici (sezione / lunghezza condotti vs. pulsazioni aria) AH	rispettare posizione limite BAA	generare moto (rispettare linearità) BAB	trasmettere moto (rispettare isteresi) BAC	segnale di comando BBA	segnale di feedback BBB	vincoli geometrici in funzione richiesta cliente BC	circuiti aria CA	circuiti acqua CB
CAD 241 Completo	1	**CW 0083677 I**	0											
O-Ring Gasket	4	EN 0011668 B	1											
Screw Self-tapping sensor fixing	1	CM 0018008 B	2											
Screw Electro-Mechanic/Actuator fixing	2	CM 0018875 A	3											
T-MAP Air Sensore	1	CA 0084845 A	4											
Screw Self-tapping	2	CM 0081426 A	5											
Double lip seal (gasket)	4	EN 0086402 A	6											
Screw	10	CM 0090608 A	7											
Bush for throttle shaft seat	4	AF 0086412 B	8					v						
Throttle valve	4	BR 0086407 D	9					v					v	
Variable Swirl Throttles Actuator Assebly	1	HC 0090567 B	10					v						
Bracket-Throttle valve shaft actuator	1	CE 0083969 G	11					v						
Bracket-Actuator support	1	CE 0084049 F	12					v						
Comolded Shaft/Throttle valve	4	AA 0086408 E	13					v						
Flange	1	BB 0083954 G	14					v						
Air Intake Manifold Assembly	1	CX 0091492 F	15	v	v	v							v	
Cylindrical Bush	9	AF 0083701 A	16											

Fig. 7: Correlation matrix between functions and components

At the same time, the correlation matrix also permits a preliminary evaluation of complexity for each function or component counting:

- how many components are involved in the same sub function ("function's complexity")
- how many functions use a specific component ("component's complexity")

In this way, it is trouble-free to recognize and rank functions/components respect to complexity.

In the specific case of our Throttle Body, using the previous method for reliability evaluation of every component, it was possible to calculate the reliability of the sub functions combining the contribution of every component that participates in them. And combining the contribution of every sub function, it was also calculated the reliability, alias "frequency of fails", for each main function.

In the third step, another tool of Design for Quality, the Design Failure Mode and Effect Analysis (DFMEA), was used to define the "gravity of fails" of functions that represent an important standard parameter able to indicate the criticality (in term of impact on users) of each failure. Using these two indicators (frequency and gravity), critical functions and components were highlighted and ranked in a quick and objective way, creating a roadmap to distinguish which component has to be experimentally tested in order to improve the reliability of each critical function. In this way, it was possible to limit the number of components of interest, reducing time and cost for the following experiments.

RELIABILITY FROM EXPERIMENTS

Between several components that were experimentally tested, the double-effect torsional spring (fig. 8), here proposed for discussion represent a particularly interesting case.

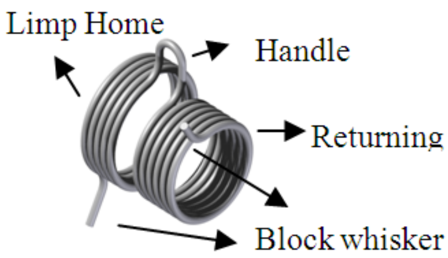

Fig. 8: Double torsion spring with its two parts of "Limp Home" and "Returning"

The double torsion action realized by the spring can be functionally divided in two loading phases, under and over a defined position, called limp-home (LH), and the fast, complete returning stroke (RS) to the initial, preloaded zero-position. Different components failed during the ordinary experimental validation tests (inside the factory) under a combination of fast opening-closing movements, temperature cycles and vibrational stresses.

These fails were considered unexpected and inexplicable since millions of sample for this kind of spring had been produced, tested, installed and used by end-users for more than 10 years without any particular reliability problem. Neither modifications in design had been introduced, nor modification in testing procedures or in manufacturing had been revealed. Ordinary tests were not useful for further investigations since they were performed on the whole system (throttle body) with the limits to be expensive, time-consuming and with a low number of samples (unable to find a fails with few PPMs of occurancy).

Then, DoE and ALT techniques are basically requests. Specific technical solutions had to be used to design and realized an experimental equipment able to perform, at the same time, fatigue tests on a large number of torsion springs. Statistical tools had to be used to evaluate the fatigue strength.

During the validation tests in factory, a rigid support fastened each throttle body simulating the air manifold flange on the engine. These accelerated fatigue tests were realized using mechanical movements, thermal cycles and sinusoidal vibration. Test time was set to 300h with a bulk temperature daily varying from -40°C to 140°C and 3-axial vibrations. Acceleration wave band was from 20Hz to 225Hz with a frequency vibration speed of 1 oct./min.

The particular stroke intensity cycle had a complex shape. Under these conditions, 50% steel springs failed the validation tests stopping to work after different times of testing.

In our case, extracting the "part" (the spring) from the "whole" (the throttle body) permitted to strongly simplify the experimental conditions, leading to simpler experimental equipments. For example, considering these springs are realized by cold drawn steel wire with a 1,6mm diameter UNI EN 10088-3 X 10CrNi 18-8, the thermo-mechanic modifications related to daily cycle of temperature were considered not relevant (beyond the little thermal deformations in geometries): the 140° upper limit of temperature is far away from every significant transition in mechanical proprieties of materials (not less than 250°). At the same time, both vibrations and slight specificities in loading curve were considered, in terms of stress, too low (around 0.1% of the yield stress) to create direct effects.

The study on the material behaviour and the spring functionality was also used in the aim of designing a simple testing machine [8]. The basic ideas to guide the design were functionality, easy realization and necessity of changing many springs after each test. For example, considering that only one part ("returning part") of the double spring carries the maximum stress and that every failure arises on the crossing of the returning spring and the handle, the equipment was realized around this part of the spring.

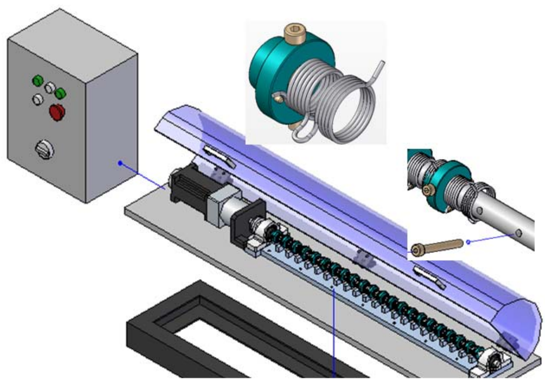

Fig. 9, the testing machine

By this kind of simplifications, it was possible to designed and realized a specific equipment for ALT (fig. 9). Around 200 springs were tested for not less than 300h (1 million of cycles) up to 1500h. A statistical analysis of the failure times was performed considering a Weibull model (but other statistical distributions could be easily taken in count) in order to get a failure probability of the part as a function of time. Depending on the logic of the experiment and on the control capability, at the end of each test, results can arise as *multiply time censored data*:

a) *censored at failure:* if it is possible to verify in each moment how many springs are unbroken. In the case of failure, one drop in the diagram of the applied moment will appear,
b) *censored at time:* if it is possible to verify how many springs are unbroken only during periodical inspections

and likelihood formulas for approximation present different shapes [2, 3, 9].

CONCLUSION

The fundamental aim of the article is to provide a direct evidence of advantages on RAM of an integrated approach. By practical examples in which theoretical and experimental methods were profitably used for reliability, safety or maintainability improving on the same automotive device in a modern approach of total quality for design and process validation.

The paper described a way to obtain a quick but approximately prediction of reliability for a complex system acquiring failure data from "the state of art". But it also proposed useful concepts how to design and develop a new equipment able to perform fast experimental testing over a high number of components in tension states similar to the reality. By experimental fails the reliability can be quickly evaluated and compared with the state-of-art for a deeper comprehension of reality.

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ПРЕГЛЕД ИНСТРУМЕНТИТЕ И МЕТОДИТЕ ЗА ПОДОБРЯВАНЕ НА НАДЕЖДНОСТТА В ТРАНСПОРТНАТА ИНДУСТРИЯ ОТ ГЛЕДНА ТОЧКА НА ПРАКТИКАТА

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Ключови думи*: пълно управление на качеството, ускорени изпитания на експлоатационния период.*

Резюме*: Докладът представя кратък преглед на инструментите и методите за подобряване както на безопасността, така и на надеждността във всички транспортни сектори (като автомобилен, железопътен, въздушен); след това предлага нов методологичен подход за съвременни научни изследвания на качеството чрез по-стриктна интеграция между теория и експерименти, като го прилага в практиката върху масово ориентирано приложение.*