Verification & Validation Plan
A Case Study of a Turbine Bucket Design Modification

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ABSTRACT

BHGE, when developing new products, verifies and validates critical system requirements of gas turbine and its own components before deploying them in the market.

In this paper a case study of Verification and Validation (V&V) approach for a gas turbine 1st Stage Bucket is presented.

One of the main requirement for this component is operative life, in particular with respect to vibrational behavior (High Cycle Fatigue): Systems Engineering approach for V&V has been applied to compare actual aeromechanical characteristics versus the ones predicted by Finite Elements Models.

As verification technique, an aeromechanical test, named "Wheel Box Test", has been performed on buckets installed on a dummy rotor: preparation, performance and results management of such test are described.

Stakeholders' requirements were finally validated on a real engine by acceptance endurance test at customer site.

INTRODUCTION

In the Oil & Gas Industry, new technology injection is key to improve plant production, equipment installation and maintenance and to increase the lifetime of parts. Machines usually operate in harsh and tough service conditions and their components are exposed to extreme thermal and mechanical loads.

Gas Turbines can be categorized among the most critical machines operating in an Oil & Gas plant, surely withstanding the toughest working conditions; they are employed to provide driving force for compressors and electrical generators, converting the chemical energy of a (usually) hydrocarbon fuel into mechanical energy.

The most critical component of a gas turbine is the 1st stage bucket: a rotating object, subject to the highest temperature and mechanical forces. Its purpose is to convert the thermodynamic energy contained in the pressurized and hot gases coming from the combustion chamber into a tangential force applied to a wheel, transformed consequently into shaft torque and then in output power.

The bucket herein described has an approximate weight of 4.5kg, spins @5100RPM on a diameter greater than 1m and is subject to a pulling centrifugal force of about 65 tons each (there are 80 buckets on the wheel) and a temperature of ~900°C.

TECHNICAL PROCESSES: STAKEHOLDERS' NEEDS, SYSTEM REQUIREMENTS AND DESIGN DEFINITION

STAKEHOLDERS' NEEDS: *The needs fulfilled by this project come, following a market analysis, from the Product Leadership internal to the company; the new bucket shall:*

- *Assure the same parts life (buckets and wheel) and operation*
- *Reduce the risk of failure (cover plates)*
- *Simplify the assembly procedure*
- *Improve parts management*
- *Reduce parts cost*
- *Be fully interchangeable with baseline bucket*

SYSTEM REQUIREMENTS: *These needs have been translated into the following system requirements:*

1. *Typical failure modes shall fall within internal Design Practices limits*
2. *Bucket weight and center of mass shall not change (or improved at most) not to negatively affect stresses on wheel*
3. *Cover plates shall be integrated into bucket casting*
4. *Interfaces with surrounding components shall not change*

DESIGN DEFINITION: *Having considered the bucket as the System of Interest, its features have been drilled down; since the sequential approach has been utilized, detailed features have been reported in the Vee diagram.*

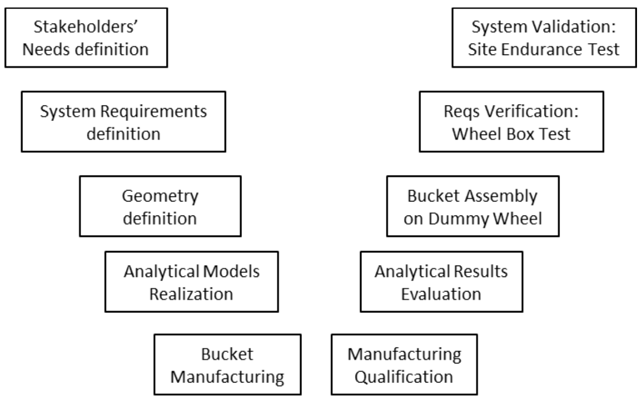

Figure 1 – Vee Diagram [1]

As per system requirements, new bucket design provides for the elimination of cover plates as separate components, becoming integrated in the body of the bucket itself, without any impact on performances and life cycle of the part.

It covers the needs for increased quality, reliability and parts management as well as cost reduction: integrated cover plates allow an easier, faster and error-proof installation (with a reduced number of parts, from 5 to 1) while safeguarding full interchangeability with current design; reduction of part numbers brings a significant improvement in warehouse management and makes the buckets kit cheaper than baseline.

In Figure 2 a comparison between baseline bucket with separated cover plates (the latter in red) on the left and the new design bucket on the right.

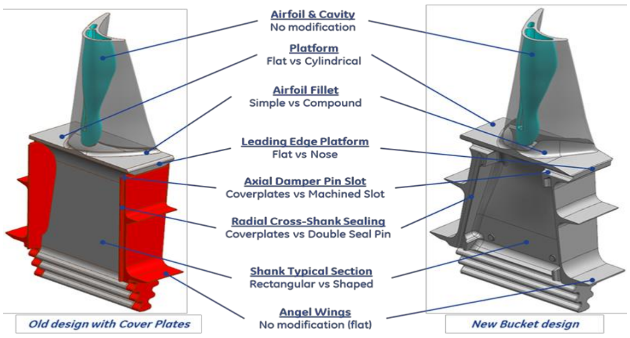

Figure 2 – Buckets Comparison

Verification & Validation Plan

Numerical simulations have been developed and used to analyze operating thermal and mechanical loads, verify interfaces with surrounding components (clearances) and check the aeromechanical behavior and damping effect (provided by pins, installed between buckets, that dissipate vibration energy by friction, reducing vibration amplitude) to accurately evaluate the robustness of the design and ultimately to verify it against the typical failure modes of a turbine bucket.

A correct aeromechanical evaluation of the bucket is important to avoid the High Cycle Fatigue (HCF) phenomenon to be catastrophic for the bucket itself (bucket failure means GT failure).

Typically, the design of a new GT bucket is verified and validated, from the aeromechanical standpoint, by a Full Engine Test, meaning that an entire gas turbine must be instrumented, installed on a test bench capable of full speed/full load operation and run for the amount of time needed to gather all necessary data: roughly this requires 1 year for preparation and execution and costs around 5M€.

The application of Systems Engineering principles allowed the avoidance of the Full Engine Test in favor of an easier and cheaper aeromechanical test, named Wheel Box Test (WBT), for requirements verification, followed by and endurance test at customer site for stakeholders' needs validation.

Verification - Wheel Box Test: *together with system requirements definition, the characteristics of aeromechanical test have been developed; among the others, the main features of the verification method included:*

- *Possibility to test baseline and new design buckets at the same time*
- *Possibility to test different damper pins*
- *Possibility to easily change forcing frequencies*
- *Possibility to verify real damping effect (use air instead of oil as forcing mean)*

Test facility was scouted, and test campaign was designed and realized in close collaboration with facility owners; main activities during preparation phase included but were not limited to: test cell architecture evaluation, interfaces management, special components design and manufacturing, data collection system evaluation, safety procedures establishment (e.g. LOTO).

Critical, during this phase, was the evaluation of the architecture of data storage and data sharing procedures: starting from the raw data, a first elaboration was done directly by the acquisition personnel, then data was transferred for the final post processing and data matching.

A final review with Chief Engineers, including data from previous tests done on baseline bucket, confirmed the alignment between analytical models and test results, closing the verification phase.

Figure 3 – Wheel Box Test – Test Cell

Validation – Site Endurance Test: *the new bucket has been then installed on a real engine at customer site for the validation.*

The unit was chosen since it is constantly monitored by remote diagnostic: a bunch of parameters were selected to be kept under control by engineering department, confirming all operational parameters inside the limits.

Boroscope inspection was done to verify the interfaces with surrounding components.

Completion of several thousands of running hours validated the aeromechanical behavior (in case of resonance, HCF takes few hours to reach a catastrophic failure).

Change Management

New bucket has been introduced issuing new part codes and passing through Product Configuration Board (PCB), a process that involves an interdisciplinary team to evaluate all the impacts of the change: supply chain (supplier qualification), warehouse management (old parts depletion), fleet impact (service bulletin).

Conclusions

For this project the right definition of a suitable Verification and Validation plan was key from the very beginning, since the "usual" testing method (engine test) was not affordable and, without an alternative, this situation would have stopped the project.

Moving from stakeholders' needs and together with system requirements definition, the V&V plan was determined, starting the test facility scouting and test preparation in the earliest phases of the project.

Test preparation and execution absorbed a quite huge portion of resources dedicated to this project, in terms of budget and engineering efforts, but test outcomes were really satisfying and allowed, for the first time in BHGE, to release the design of such a critical gas turbine component without an in-house full engine test.

References

[1] INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, 4th edition