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COMBUSTION HARDWARE EXTENDOR KIT III ENHANCEMENT KIT FOR MS5002C & D HEAVY DUTY GAS TURBINE FOR OIL&GAS APPLICATIONS

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ABSTRACT

The continuous increase of both energy demand and oil and gas prices has driven gas turbine operators to seek improvements in both the durability and performances of their machines. The maintenance interval still represents one of the most critical issues related to durability and has a strong impact on production costs, especially in oil and gas applications.

To address this issue, specific development programs were introduced by GE Oil & Gas, aimed at extending the mean time between maintenance (MTBM) of its entire heavy-duty fleet.

These programs basically consist of identifying the most probable failure modes, strategies to remedy problems and finally delivering new technology. The success of such programs starts with the introduction of the new product, after it has gone through a rigorous and well-proven design process which includes conceptual, preliminary and detailed design reviews.

Due to both high temperature environment and combustion dynamic frequencies, the combustor hardware is prone to different failure modes, limiting, in some cases, the MTBM to a relatively small number of hours.

This paper describes the design process followed to deliver Extendor[tm] III, which is a modification kit for the LHE (Lean Head End) combustion system of the MS5002C & D heavy duty gas turbines, aimed at enhancing MTBM.

The development strategy is described in detail and the results of numerical dynamic analyses and validation testing are shown.

NOMENCLATURE

FEM	Finite Element Method
FRF	Frequency Response Function
GT	Gas Turbine
H	Material Hardness
HCF	High Cycle Fatigue
j	Film Thickness
K	Wear Coefficient
L	Load
LCF	Low Cycle Fatigue
LHE	Lean Head End
LPT	Low Pressure Turbine
MA	Modal Analysis
MTBM	Mean Time Between Maintenance
T	Temperature
TP	Transition Piece
t	Time
V	Velocity
W	Wear
α	Environmental Effects
β	Geometric Effects
Φ	Finish Factor

INTRODUCTION

The duration of the mean time between successive maintenance shutdowns is a key qualification for a heavy-duty gas turbine, especially in oil and gas applications.

As for all engine components, the combustion hardware needs to be inspected, checked and then, at the end of its life cycle, replaced. To keep the engine reliable and efficient, a designated maintenance plan has to be followed, which at a minimum involves inspections that require periodic shutdowns. Thus, the maintenance plan has to be tuned to customer needs, challenging engineers to more robust concepts, with respect to the possible failure modes.

An increasing number of surveys have been launched in recent years, focused on the identification of the best design practice for gas turbine components from the perspective of long life. In particular, combustion systems are very critical components, because of the high temperatures and heat fluxes loading the different components. In addition, components like can shaped liners are usually thin, and constraining joints are designed to reduce thermal growth induced stresses. Such constraint could bring the natural frequencies of these assemblies close to the band-width of pressure dynamics caused by heat release fluctuations; the resulting signal becomes an important forcing function for structural vibration modes.

Nowadays, especially in combustion systems, high cycle fatigue (HCF) is recognized as one of the most common failure modes in dynamic systems, enhancing fretting wear (W) at the joints for different components of the assembly.

From the GE fleet of heavy duty engines, the MS5002C & D were selected to be part of a life extension program because they are in common use by many oil and gas customers.

The general approach for the life improvement program, which has been tailored to provide the best solution to meet customer needs, will be described from field fleet assessment to the analytical modeling steps and materials testing.

To extend the MTBM of the combustion component's a specific set of goals were defined from a business analysis. Starting from the MTBM of a previous successfully delivered Extendor^{tm} kit as a reference, the customer needs were analysed, along with different maintenance plans, with the objective of minimizing the number of scheduled stops necessary. An MTBM was selected to establish the durability targets for all combustor components.

Keeping retrofit-ability as one of the main constraints, various concepts, basically differing according to the position and type of joints, were selected for deeper investigation. All of the concepts had their origin in other existing engines and were then fitted into various assembly configurations and dynamically assessed.

The assessment was carried out with the help of numerical modal analysis, namely a finite element analysis (FEA), whose assumptions related to the critical joints were proven using a dedicated methodology. The dynamic validation was supported by a test campaign, a dynamic characterization of the combustion assembly and a material test campaign focused on a design to reduce wear.

MS5002 HEAVY-DUTY GAS TURBINE

The MS5002 is one of the most successful gas turbines for mechanical drive applications in the 30 MW class. Since 1970 GE Oil and Gas has shipped more than 620 units, and millions of trouble-free operating hours have been logged. In response to market needs the MS5002 has undergone a series of upgrades represented by the B, C models and most recently the MS5002D and MS5002D+ (Power Crystal).

The D model was rated at 43,000 HP with a heat rate of 8,650 BTU/HP-hr and is the most powerful and efficient configuration in the MS5002 family. The D model is based on GE Oil and Gas most recent achievements from advanced aerodynamic axial compressor design and extensive experience in gas turbines for oil and gas applications, and combines the proven design concepts of scaling with the state-of-the-art in materials, cooling/sealing technology and design techniques.

General Electric began the development of the MS5002 in 1969. The first Frame 5 two-shaft models, the MS5002A and MS5002B, were developed simultaneously to take advantage of the highly successful single-shaft 5001M and N compressor designs. In 1987 the MS5002B rating was increased to 38,000 HP as the MS5002C, through the application of advanced materials technology and design features that were more resistant to high temperature damage and wear.

The MS5002D represents the latest joint development by GE Energy and GE Oil & Gas. The most significant feature of the MS5002D up rate is the replacement of the MS5002 compressor section with a slightly modified 17 stage compressor derived from the MS6001B and new compressor rotor/stator blading and casings. The up rating to a modified MS6001B compressor increased the airflow and results in an increased pressure ratio and thus power.

The output is further increased with a new first stage nozzle design with a reduced throat area which fully exploits the higher pressure ratio of the new axial compressor while limiting the maximum firing temperature rise to a level acceptable for reliability of nozzles and buckets. Even though the nozzle replacement was not needed for a C to D retrofit an additional power increase of 0.75% was obtained.

Advanced seals for the high pressure packing, No.2 bearing, and Stage 2 shrouds provide an additional performance improvement. The design change to the new MS5002D 17 stage compressor requires replacement of the compressor rotor/stator blading and casings.

Table 1: Comparison of MS5002 performance features

	MS5002A	MS5002B	MS5002C	MS5002D
Compressor Stages	15	16	16	17
Pressure Ratio	7.4	8.8	8.8	10.75
Firing Temperature (°C - °F)	921-1690	927-1700	966-1770	986-1807
Exhaust Temperature (°C - °F)	524-975	491-915	516-961	510-950
Air Flow (10^3 Kg/hr) - (10^3 Lb/hr)	351-773	438-966	445-982	504-1113
Output (kW - hp)	19.575-26.250	26.100-35.000	28.337-38.000	32.066-43.000
Heat Rate (kJ/kW-h - Btu/hp-h)	13.837-9.780	12.493-8.830	12.309-8.700	12.235-8.650

Three major changes differentiate the advanced technology combustion liners of the MS5002C & D from previous designs.

These changes are TB coating, hard-facing on the collars and crossfire tubes, and splash plate cooling around the crossfire tube collar. Splash plate cooling and hard facing mitigates cracking in critical areas of the liner such as the louvers and dilution/mixing hole region.

Regarding the enhancement of maintenance intervals a first step on increasing MTBM had already been made with the introduction of the Extendor^{tm} + kit achieving the target of 24Khours for both Liner and TP.

Hastelloy-X was retained as it provides excellent tolerance to high temperatures and has good crack resistance. Wear and crack resistance were improved with a new floating inner seal design with side seals and increased corner radii on the aft frame.

MTBM ENHANCEMENT STRATEGY

Table 2 shows durability performance for the existing MS5002D LHE combustion system (Not Extendor[tm] and Extendor[tm] +) and, highlighted, the targets for Extendor[tm] kit III:

Table 2: MS5002D LHE durability performance

MS5002C/D LHE Combustion Systems	Performance (MTBM)
Not Extendor[tm]	Liner: 12Kh TP: 24Kh
Extendor[tm] +	Liner: 24Kh TP: 24Kh
Extendor[tm] III	**Liner: 24Kh** **TP: 48Kh**

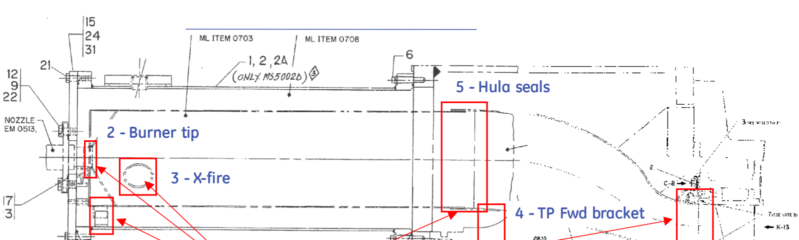
The main targets of the Extendor[tm] kit III program were:

- MTBM: 24Kh for Liner and 48Kh for TP
- Retrofit able solution

The initial steps were as follows:

- Survey of applicable lessons learned and field experience
- Strategy definition

Analysing field data for wear at mechanical contacts for different combustion components highlighted this as a principle failure mode for reaching the MTBM target for the TP. The list of failure modes together with most critical contact interfaces of the combustion assembly are shown in Figure 1.



MS5002D LHE (Not Extendor[tm] kit & Extendor[tm] kit 1)		
Failure mode	Field experience	Areas of improvements
Wear	Yes	New design
LCF	No	no changes on max cycles as per prod. Spec.
HCF	No	-
Oxidation	No	Assessment due to target life on TP
Creep	No	Assessment due to target life on TP

Fig. 1: Combustion assembly critical failure modes

Tribology is the science and technology of interacting surfaces in relative motion and relates in particular to the understanding and the analysis of wear mechanisms [1,2]. Quantitative values for friction and wear depend on the following basic groups of parameters:

- Structure of the system: components and their relevant properties
- Operating variables: loads, kinematics, temperature and time
- Mutual interaction of the system components

In general wear is given by [4]:

$$W = f(\alpha, \beta, \left[\frac{K\phi}{H}\right], j, L, V, T, t) \qquad (1)$$

From metallographic inspections carried out on the hardware dismounted from the field it was possible to identify potential wear mechanisms at different coupling locations and having different relative motion. Almost everywhere sliding wear was observed and in certain locations hammering was possible as well. This means that most of the time contact surfaces move with respect to each other at the contact surface plane.
From the literature, for dry contacts, the sliding wear (adhesive wear) can be described by Archard's [1,3] formula:

$$W = K \cdot \frac{L \cdot V}{3 \cdot H} \cdot t \qquad (2)$$

According to this formula, three key approaches can be defined to reduce the wear acting on each of the above variables:

- *Increase material hardness*: through a dedicated wear test campaign to evaluate the wear behaviour of different base material-hard coating combinations at different combustor locations. Several specimens representing a baseline and new couplings were tested under sliding wear at defined loads and temperatures. The target of this activity was to select the coating for wear couplings.
- *Decrease relative displacements/velocity*: through FEA, different solutions for the combustion assembly were evaluated in terms of natural frequencies and mode shapes. Down selection was driven by the desired margin between combustion hardware natural frequencies and forcing functions (typically dynamic pressure oscillation).
- *Redesign contact interfaces:* to reduce contact pressure and clearances.

WEAR RESISTANT MATERIAL TEST CAMPAIGN

In order to recreate the wear conditions observed on service components a custom-built reciprocating test fixture was designed and build. This could be attached to a standard hydraulic test frame and contained a furnace to enclose the samples for high temperature tests. A picture of the test fixture is given in Figure 2. It consists of a block specimen, which is fixed to the actuator of the frame, and a shoe specimen, which is loaded against the block through an independent hydraulic actuator. The shafts that hold the block and shoe specimens are supported on closely machined graphite bearings imparting low friction motion in the axial direction while restricting motion in the radial direction. This assembly is enclosed in a furnace that can be heated to a temperature of up to 600 ^{o}C. The block and shoe holders have threaded bars that extend out of the furnace for making displacement measurements using lasers mounted on the fixed base plate of the frame. This provides an accurate, independent measurement of the relative slip between the two specimens.

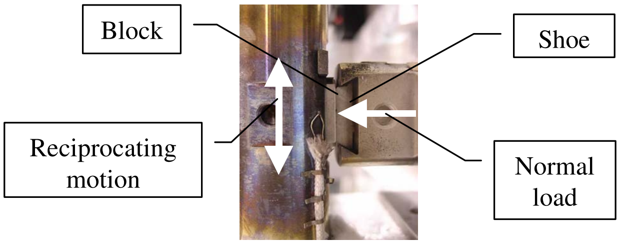


Fig. 2: Close-up of the block and shoe fixtures on the test rig

The block and shoe specimens are mounted on their respective holders and are locked in place using wedges. Full contact between the test specimens is ensured at room temperature by using shims and adjusting screws in the shoe fixture. Once alignment is achieved, the furnace is closed around the samples and heated to desired temperature. The slip distance is set through the test frame by measuring the difference between the laser reflected off the shoe specimen holder (fixed) and the laser reflected off the block specimen (moving). The load, temperature, slip distance and frequency are set and the test is carried out for the desired number of cycles, typically several million cycles. Force sensors on the actuators capture the horizontal and vertical forces on the specimens.

The test conditions for this study are shown in Table 3. These conditions were chosen by appropriate scaling of typical values seen in field hardware at the relevant locations.

Table 3: Parameters used in the tests

Test parameter	Value
Normal Load	200 N
Temperature	350 - 550°C
Slip Distance	0.5 mm
Frequency	15 Hz
Number of Cycles	3 and 10 million

In addition to the usual weight measurement before and after testing, the surface roughness was also measured at three locations representing the top, middle and bottom of the wear contact in the width direction. In this way, both weight loss (which is converted to volume loss and reported later) and change in the average roughness after the test could be calculated. Volume loss measurements were sometimes inconclusive due to material transfer between the specimens; hence, an additional measurement of the deepest pit depth was carried out using stylus profilometry. Several traces were taken in the length and width directions across the wear scar and the deepest measurement was taken for analysis. A reference was taken from unworn areas of the block and shoe specimens from which the pit depth could be measured. Cross-section metallography was performed on the worn block and shoe specimens to understand the wear mechanisms and sub-surface damage incubation. Optical microscopy followed by SEM / EDAX characterization was used to characterize the samples.

A broad test matrix was defined, based on a comparison of the actual materials used in previous MS5002 designs and a set of innovative, but commercially available, metals/coatings.

Different combinations of Iron-based, Ni-based and Co-based alloys were included in the test as well as various compositions of thermal spray coatings.

The results of the wear test campaign showed the superior performance of Co-alloys and Tungsten carbides (WC)-Co HVOF (High velocity oxygen fuel) coatings.

Depending on the wear location testing conditions, metals or coatings were determined to be the best design choice.

The final material selection was based on the material properties and manufacturing consideration.

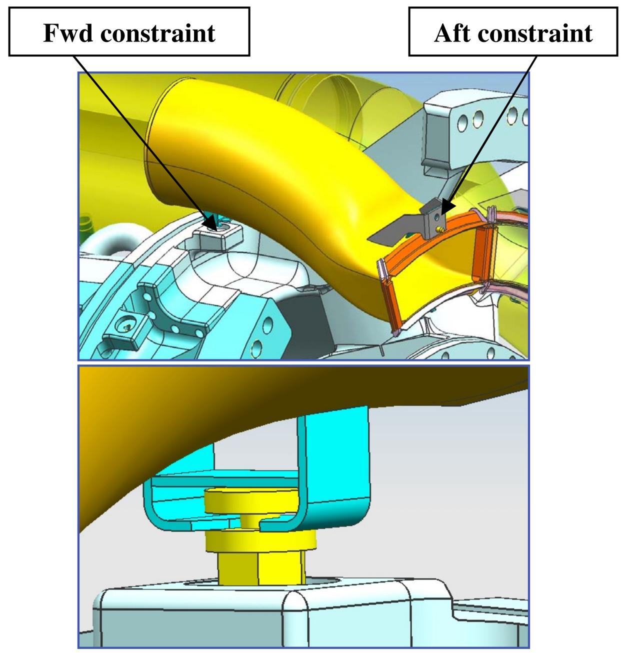


Fig. 3: MS5002D baseline configuration

DYNAMIC ANALYSIS OF DIFFERENT CONCEPTS

Based on the wear rate evaluated from field results, wear was predicted to determine if it were possible to reach the program target with the existing Extendor^{tm} kit hardware. The results of this analysis were: the target of 24Kh was achievable for the liner, while the old TP hardware was not able to reach 48Kh. Therefore a new design was required for the TP.

The MS5002D TP configuration (hereafter referred as the baseline) is connected to the rest of the engine at two locations (Figure 3): a Fwd constraint to the axial compressor casing (through a pin locator-bracket) and an Aft constraint to the HP nozzle ring (through aft bracket). The joint between the TP and the HP nozzle ring is achieved through a bolted connection. On the engines in the field the connection is made through a single bolt so the HP nozzle ring had 12 holes (one for each can).

A benchmark study was conducted to identify different Extendor^{tm} kit layouts from the GE heavy duty family which could be suitably adapted for the MS5002D TP. The field experience related to each of the analysed layouts was retrieved, i.e. the firing hours reached and observations on the hardware made on disassembled parts.

Examples of alternate layouts considered are reported in Figures 4 and 5:

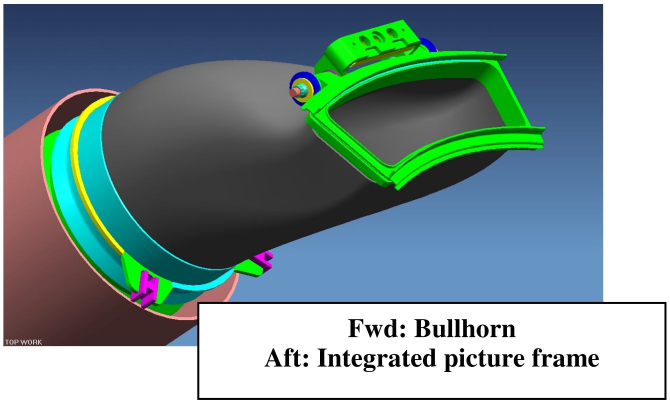


Fig. 4: MS6001B solution

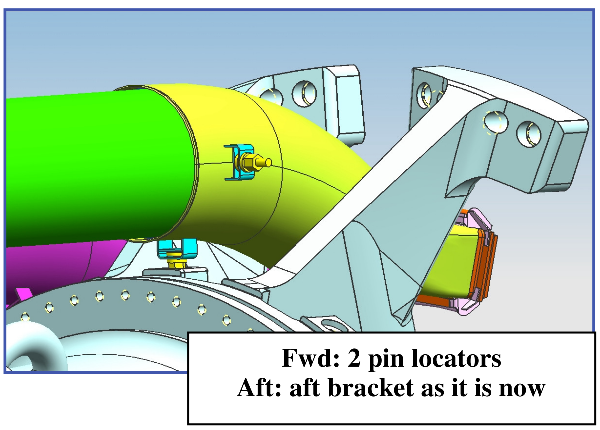


Fig. 5: MS5001 solution

Different TP design solutions are summarized in table 4:

Table 4: TP design options

Solutions:	**A**	**B**	**C**
Inlet: **Mouth**	Baseline design	Forged	Fr6 design
Fwd : **Constr.**	Ext+ Design	Bullhorn	Double90° Brackets
Aft: **Constr.**	Ext+ Design	Integral as Fr6	

Based on technical assessments every design solution was evaluated by assigning a rating to generate a list of the best solutions at different locations.

By combining all the best design solutions, it was possible to define several design configurations to be evaluated and compared. The design solutions are summarized in the table 5 and a graphical representation is given in the overall configuration details reported in Figure 6:

Table 5: TP design configurations

Config.	**Inlet Mouth**	**Fwd Constr.**	**Aft Constr.**
1	Forged	Bullhorn	Ext+
2	Forged	Double90°-brackets	Ext +
3	Forged	Bullhorn	Integral as Fr6
4	Forged	Double90°-brackets	Integral as Fr6

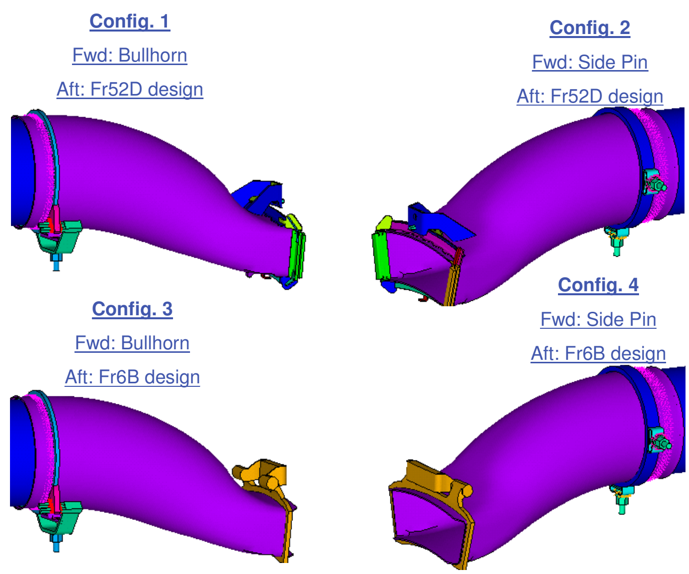


Fig. 6: Overall configuration details

With the support of one of the GE Research Centres a modal analysis was carried out on the first release of assembly models (Figure 7) for each configuration to obtain the natural frequencies and modal shape, and to evaluate margin with respect to dynamic pressure oscillation and rotor dynamic forcing sources.

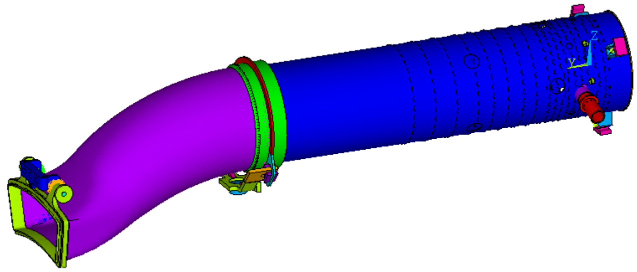


Fig. 7: MS5002D LHE assembly model

The dynamic response of the overall assembly was simulated fusing a linear model, though friction and hammering cause the actual behaviour of the constraints to be non-linear. The natural frequencies of the combustion hardware as well as the related modal shapes were calibrated against a cold impact test. In the Finite Elements method (FEM) linear elements must be used for the modal and harmonic analysis: therefore spring elements were introduced to simulate mechanical couplings by defining normal and sliding spring stiffness.

The dynamic characterization of the combustion hardware was carried out through a special experimental activity consisting of room temperature impact tests performed in two steps:

1st step: impact test on each combustion assembly component in an unconstrained configuration (free-free). The following components were tested:

- Liner
- TP baseline configuration
- TP proposed configuration

2nd step: impact test on the Liner and TP assembled together by means of a hula seal joint but unconstrained with respect to the engine. The following configurations were tested:

- Liner and TP baseline configuration
- Liner and TP proposed configuration

The natural frequencies, damping and mode shapes of the structure were investigated. These measurements allowed calibration of the FEM for both the components and the assemblies, not only in terms of natural frequencies but also in terms of modal shapes.

The dynamic correlation of the mode shapes for the FEM and test was verified through the MAC (Modal Assurance Criterion) index, defined as follows:

$$MAC_{ij} = \frac{\left| \{\psi_i^{test}\}\{\psi_j^{FE}\}^* \right|^2}{\left(\{\psi_i^{test}\}\{\psi_i^{test}\}^*\right)\left(\{\psi_j^{FE}\}\{\psi_j^{FE}\}^*\right)} \qquad (3)$$

where ψ_i^{test} and ψ_j^{FE} are the displacement vectors, in the accelerometer locations, representing the mode shapes of the FEM and test models, and shows if two vectors are orthogonal or parallel. The MAC values are between 0 and 1 where a MAC close to 1 means perfect mode shapes correlation (vectors are parallel); whereas a MAC close to 0 means that the mode shapes are completely different (vectors are orthogonal).

MAC values above 0.7 have been considered to be indicative of well-correlated models and values below 0.5 are related to poorly correlated models.
The final correlation results showed a very good match between the FEM and test models (Table 6).

Table 6: MAC values for liner and TP free-free assembly

Mode #	MAC Value (FEM-Test)	Natural frequency D(FEM-Test) %
1	0.85	3.2
2	0.97	1.3
3	0.78	1.5
4	0.72	1.6
5	0.94	3.1
6	0.90	0.9
7	0.78	6.9
8	0.78	9.9
9	0.79	0.1
10	0.96	3.6

The calibrated model was run including the metal temperature effect: it was observed a drop in the value of the frequencies (by approx. 15Hz) while modal shapes remain consistently the same respect to those at room temperature. Different constraint configuration models were built up to evaluate the sensitivity to constraint variability. The simulation plan facilitated the selection of the constraint configuration and the spring stiffness. Then, analyses were run for each configuration varying the Fwd constraint contact stiffness to evaluate sensitivity.

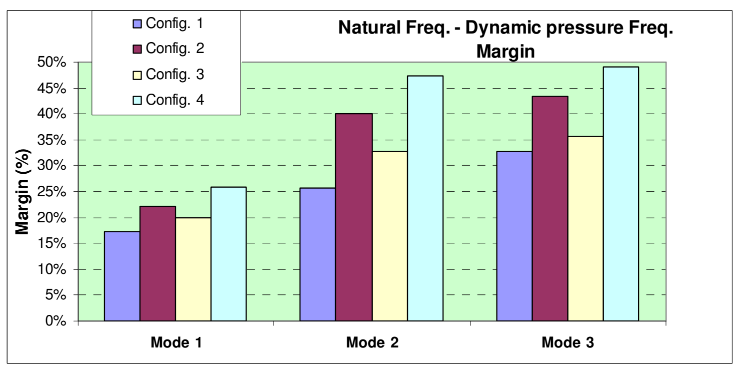


Fig. 8: Modal analysis results (preliminary models)

Figure 8 shows the modal analysis results for the selected configurations in terms of the relative margin of the frequency to dynamic pressure fluctuations. Keeping retrofitability and cost as design constraints, concepts were evaluated and weights assigned. Configuration 3 of Figure 9, similar to the one already adopted for Extendor^{tm} kit for the large frames was selected. Preliminary and detailed analyses were carried out on this configuration to get the final layout of the TP to complete the design process. Finally on the prototype of the selected configuration a cold impact test was done and its results compared with the baseline. Figure 10 shows the comparison in terms of FRF. First natural frequency of the selected configuration shifts at higher value as predicted confirming an increased margin with respect to dynamic pressure oscillations.

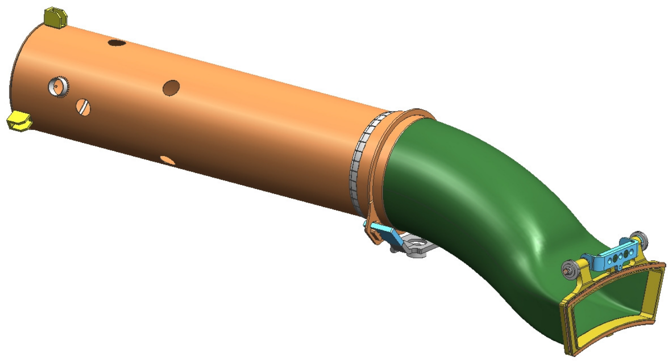


Fig. 9: Proposed MS5002D Liner+TP assembly configuration

CONCLUSIONS

MTBM is one of the key qualifications for heavy-duty gas turbines, especially in oil and gas applications. This paper describes the development steps to enhance the durability of an heavy-duty gas turbine combustor. Wear turned out to be the most critical aspect for achieving the requirements.

The dynamic behaviour of combustor components was investigated since it was found to be the principal cause of wear. Consequently, a specific numerical analysis was performed to evaluate the dynamic response of the current combustion system, as well as to investigate and verify new concepts. The analysis was followed by a validation test campaign to develop an accurate correlation between numerical and experimental data in terms of modal shapes and frequencies.

The new configuration selected was evaluated based on the predicted margin between natural and forcing function frequencies, retrofitability of the system and costs.

A parallel material test campaign carried through a on sliding wear evaluation provided a selection of coatings that could be employed.

After several design reviews, the proposed solution was implemented as Extendor^{tm} kit III for MS5002D engines equipped with LHE combustion system.

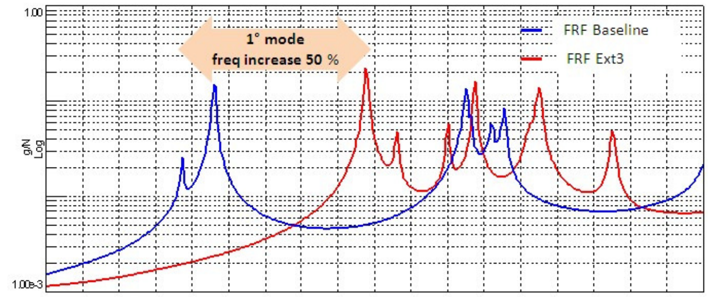


Fig. 10: Impact test in cold conditions-assembly FRF

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REFERENCES

[1] Stolarski, T. A., (1990). “Tribology in Machine Design”, Butterworth-Heinemann Oxford OX2 8DP

[2] Neale, M. J., (2001) “The Tribology Handbook”, Butterworth Heinemann

[3] Archard, J.F. (1953), “Contact and rubbing of flat surfaces”, J. Appl. Phys., 24 981-988

[4] Bayer, R.G., “Mechanical wear prediction and prevention”, Marcel Dekker, NY, 280