INNOVATIVE METHODOLOGY FOR FATIGUE CRACKING ASSESSMENT OF GAS LOADED ACCUMULATOR'S SEPARATOR USING ACCELERATED ENDURANCE TESTING

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Abstract An innovative methodology for fatigue cracking assessment of gas loaded accumulator's separator used in severe environment is considered. The accelerated endurance testing on accumulator bladder component (separator), made with rubber material, has proven that it is possible to produce in reasonable testing time the experienced fatigue cracking in service. Based on that and new complex simulation techniques, a methodology has been built in order to predict the reliability of bladder accumulator in the case of either both a new bladder material and design or new solicitation conditions. This work has permitted to develop a new modelling of the accelerated endurance test bench using mult-physic approach. This approach using the Coupled Eulerian Lagrangian (CEL) technique available in Abaqus FE code has been conducted to simulate both the fluid domain and structure domain as well as their interaction, allowing to take into account the real loading produced by the fluid solid interaction.
The numerical results have shown clearly the predictive capability of this modelling for the representation of the real behaviour of the test bench. The model has permitted also to give a degree of severity between the testing and in service conditions through the MTBF estimation.

1 INTRODUCTION

In hydraulic system circuits requiring energy storage, the gas loaded accumulators with separating elements consists of a steel shell containing two chambers for the oil and the compressed nitrogen. The gas chamber is pre-charged with compressed nitrogen through a charging check valve when the accumulator is completely empty of oil. In the case of bladder accumulator, the gas and oil chambers are separated with elastic separator (bladder). During operation, when pumping the oil to the accumulator at pressure higher than the pre-charge pressure, the oil enters the accumulator, compressing the gas and reducing the bladder volume. The oil is then stored at high pressure under the action of the compressed gas.
In some particular applications, the bladder is not subjected only to the deformation due to the storing operation described above. Other kind of solicitations must not be neglected, related to the oil movement inside the accumulator, induced during its movement. In fact, when the accumulator is in rotation around an axis, the hydrostatic pressure is varying during this rotation due the position changing of the accumulator. Therefore, even the pressure inside the bladder is in equilibrium in the storing state, the bladder is still deformed at its ends due the hydrostatic pressure fluctuations induced by the rotation. This operating condition has conducted to several cases of bladder fatigue failure mode.
Mainly, the reliability of the bladder accumulator product is driven by the bladder component, which is the main part determining both its functionality and its lifetime. The improvement of the accumulator reliability characteristics is then associated to the improvement of either the bladder material or its design.
The current approach for treating the reliability issue is to perform statistical studies made on a number of accumulators in service (in addition to accumulator product experience return), as well as accelerated endurance testing. However, the results are neither representative of a new development bladder mix nor new solicitation and environment conditions.
The main challenge is to develop a methodology based on both accelerated endurance test bench and new complex simulation techniques in order to predict the reliability of bladder accumulator in the case of new product with either new bladder material (or new bladder design) or new solicitation conditions. .
The accelerated endurance testing has proven that it is possible to produce the experienced failure modes in service, in reasonable testing time. The focussing must be given now to the numerical analysis, based on a well predictive modelling, which is the mean permitting to establish the link between the test and the service. This is also the way to establish the positioning of the severity of the accelerated test bench in accordance to the service. The loading conditions in the both situations are different and associated to the fluid movement. To lead to high accuracy of the numerical results, it is necessary to proceed to the representation of fluid part through multi-physics approach.

This article presents the proposed predictive reliability approach for fatigue cracking assessment, put in place through both the modelling of the bladder behaviour in service and the accelerated endurance test bench as well as bladder accelerated testing.

2 GENERAL METHODOLOGY

The proposed approach consists in implementing a methodology to evaluate the fatigue cracking of bladder accumulator product under real operating conditions through the reliability evaluation.
So far, the reliability of the accumulator product is determined by statistical analysis of both failures in service and accelerated testing that leads to a Mean Time Between Failure (MTBF). However, with a new bladder mix development or/and new application conditions, the MTBF assessment must be systematically reviewed.
In order to avoid this issue, the original feature of the new approach lies in taking advantage of the latest development related to both the accelerated endurance testing and the physical analysis of the bladder behaviour in the real conditions as well as in the testing conditions.
The Figure 1 summarizes the overall methodology followed for the reliability assessment, starting from the service and going to the accelerated endurance testing. The intermediate steps concern the numerical simulation of the product behaviour in both service conditions and testing conditions. Due to the complexity of the solicitation conditions, the multi-physics simulation is necessary to the achievement of the good predictive reliability assessment approach.
The finite element simulations lead to the mechanical stress and absorbed deformation energy in the bladder allowing the comparison between both in service and testing conditions. They allow also by interpreting the results through fatigue curve to predict the lifetime and the severity positioning between the real conditions and testing conditions.

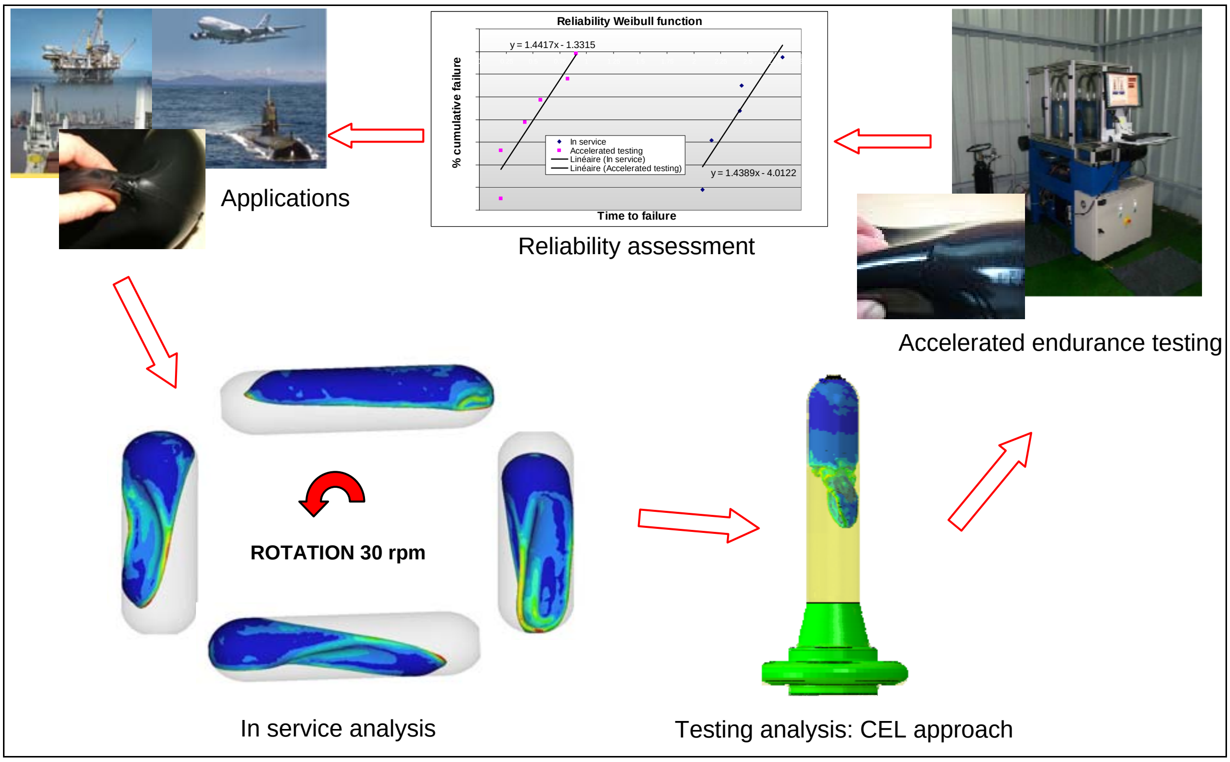


Figure 1. General flowchart of the predictive reliability method

3 REAL APPLICATION MODELLING

The application where the accumulator is in rotating movement has shown many failure cases. The associated failure modes consist on fatigue cracking due to the fluid movement inside the accumulator during rotation. In fact, when the accumulator is fixed, the oil pressure and gas pressure is in equilibrium in storing situation. However, when the accumulator is in rotation around an axis, the bladder is affected by the variation of the hydrostatic pressure of the oil column inside the accumulator. The bladder during the accumulator position changing is observing hydrostatic pressure fluctuation, leading to the closing and opening lobes on the deformed bladder. The lobes forming zones, particularly at bladder end sides, are the critical area where the fatigue cracks appear.

The first stage of the implementation of the global predictive reliablity approach is to set up the modelling of the dynamic behaviour of the bladder during the rotation. The 3D modelling of 20 Litres accumulator is performed only on both bladder and shell components. The other accumulator component is not considered.

- The bladder is represented by shell elements associated to Hyperelastic material behaviour. The internal bladder cavity is simulated with fluid element representing ideal gas behaviour.
- The shell is considered as rigid elements in contact with bladder
- The hyperelastic material behaviour is represented by Mooney Rivlin constitutive law where the material parameters are calibrated using material testing data

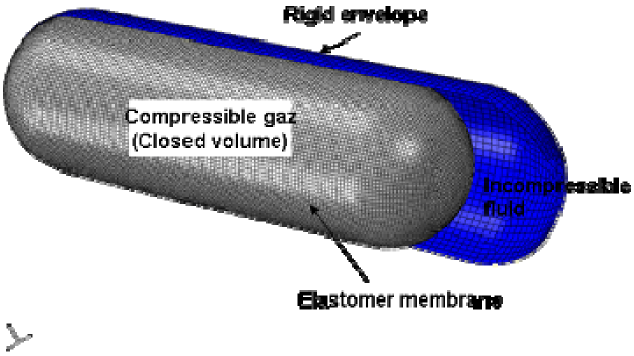
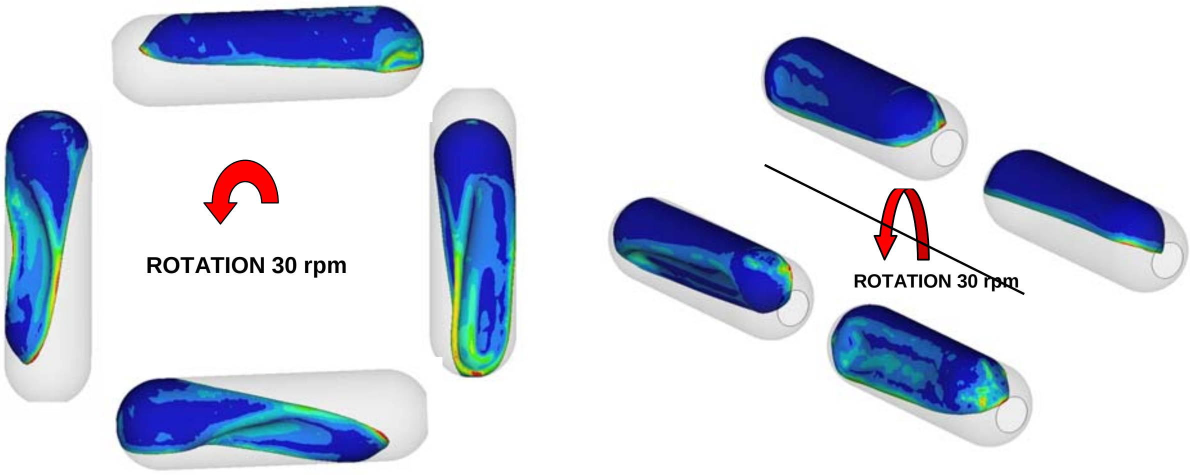


Figure 2. Modelling description

The variation of the hydrostatic pressure during accumulator is reproduced through non uniform pressure loading on the external bladder surface using Abaqus User-subroutine DVLOAD. The calculation is performed with Abaqus 6.10 FE code version. This dynamic bladder behaviour simulation in operation is performed in two calculation steps:
Step 1: Bladder crushing – lobes formation
Step 2: the first Bladder rotation at 30 rpm (from the start of rotation), inducing hydrostatic pressure variation, and leading to closing/opening lobes at the origin of fatigue failure

The Figure 3 shows the dynamic behaviour of the bladder during the first rotation for both perpendicular and parallel positioning of the accumulator with the rotation axis. It reproduces clearly the effect of hydrostatic pressure inducing lobes formation particularly at the end sides. Therefore, due to hydrostatic pressure variation, the bladder is cyclically deformed (stressed) for each rotation (one cycle), leading to a fatigue failure after a cycles number.
This behaviour is also illustrated in the Figure 4, showing the internal energy deformation cycle of the whole bladder during the rotation. Due to the difference in the design of the both end sides, the levels of the peak energy are different between the two sides. This modelling can also be used to evaluate the influencing factors on the fatigue failure modes: rotation velocity, accumulator volume, material properties and accumulator positioning. The figure 5 shows also the internal deformation evolution during rotation in the case of parallel positioning showing that this later involved less bladder deformation in comparison to the perpendicular one.



(a) (b)

Figure 3. Bladder states at different bladder rotation position for (a) perpendicular and (b) parallel positioning

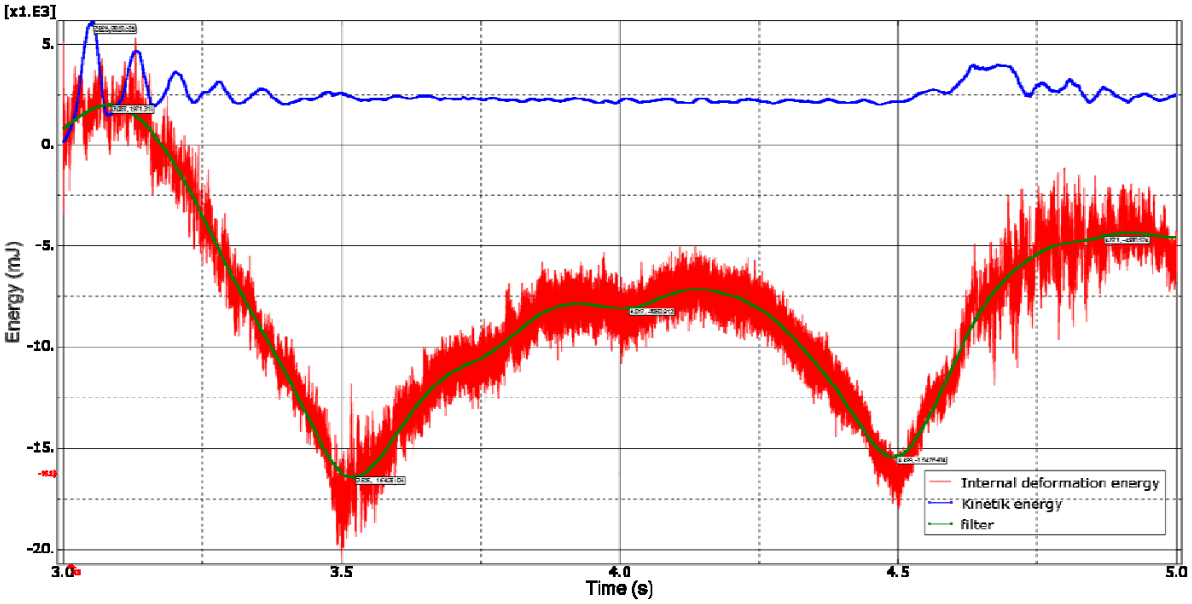


Figure 4. Evolution of the energy in service for perpendicular accumulator positioning with rotation axis

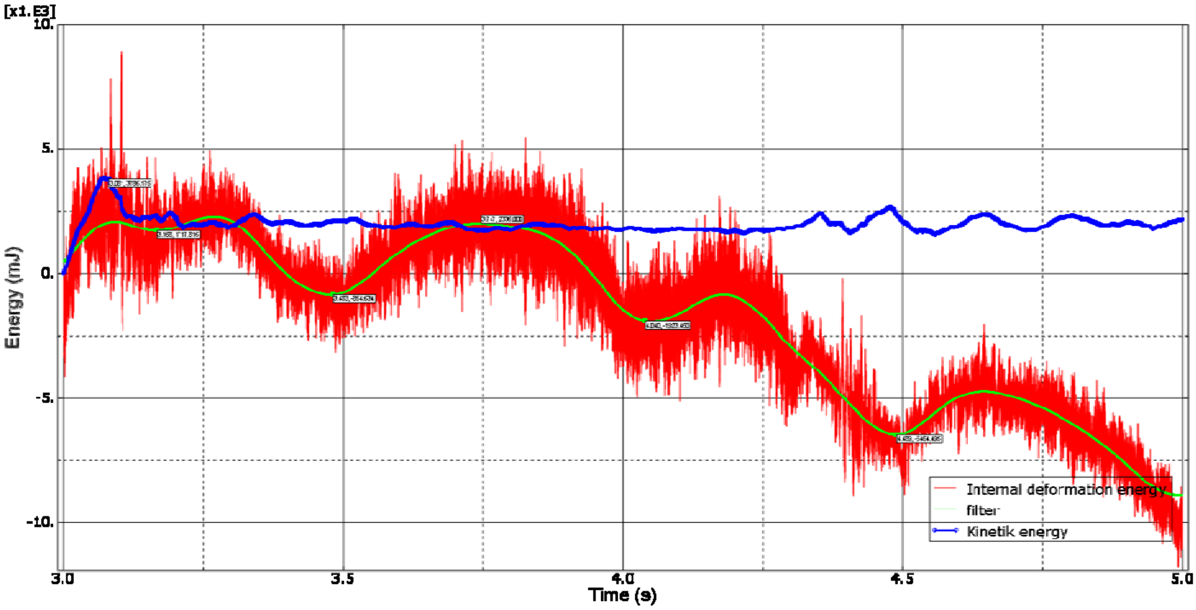


Figure 5: Evolution of the energy in service for parallel accumulator positioning with rotation axis

4 MULTI-PHYSIC MODELLING

The accelerated endurance testing is based on the cyclic strain (or stress) acceleration of the bladder, particularly in the lobes zones. This latter is not performed for hydrostatic pressure fluctuation observed in service, but by alternative fluid movement displacement impacting the bladder. By this way, the severity of solicitation is managed by both the moved oil quantity (defined volume) and velocity.

The fluid movement inside the test bench cylinders has been a unique challenge to reach a correct behaviour of the bladder. This is because it causes forces that are difficult to predict using the traditional simulation techniques. Abaqus/Explicit code includes a Coupled Eulerian-Lagrangian (CEL) capability that is useful for the representation of the fluid domain (oil) and its interaction with domain of solid structure (bladder, shell). Furthermore, the coupled domains allow modelling the deformed bladder, and the stress results can be obtained directly from the fluid movement loading simulation.

The 3D modelling of the accelerated endurance test bench is performed by integrating the main components for representing the real loading conditions

- The bladder is represented by shell elements associated to hyperelastic material behaviour. The internal bladder cavities are simulated with fluid element representing ideal gas behaviour.
- The hyperelastic material behaviour is represented by mooney rivlin constitutive law where the material parameters are calibrated using material testing data
- The oil is represented by Eulerian element (fluid domain) surrounding the bladder. The fluid behaviour is described by the Equation Of State (EOS), representing the oil flow.

This modelling has been designed in order to apply the real loading to the bladder. This latter is submitted to the fluid movement induced by the plate under the cushion. The moved oil quantity and the frequency are taken form test conditions and the corresponding velocity is imposed to this bottom plate (as shown in Figure 6).

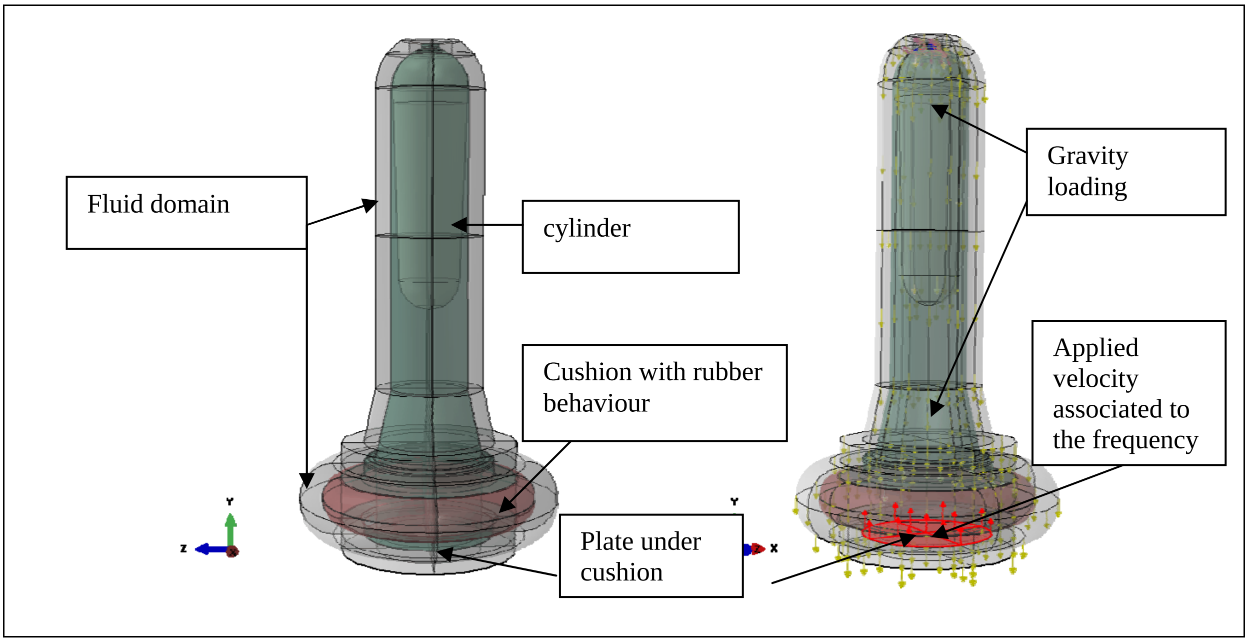


Figure 6. The test bench modelling and loading conditions

The calculation results performed with the model in the time duration of 0.4 s (frequency of 2.5 Hz) are presented in Figure 7, showing different states of the bladder deformation:

- Initial state, showing the undeformed bladder and the initial state of the oil
- The state at the starting of the fluid movement, when the global oil kinetic energy is high, the bottom of the bladder is highly deformed, as it shown during the testing observation.
- After the previous state, the oil kinetic energy decreases because of its interaction with the closed cylinder. During the oil flow decrease, the bladder is both deformed and loses its gas until the final stage.

This behaviour is also illustrated in the evolution of the internal deformation energy (Figure 8), where a maximum energy is reached at the early phase of the fluid movement, and associated to the oil maximum kinetic energy absorbed by the deformation of the bottom of the bladder. After this maximum, the kinetic energy is decreased and the bladder deformation is increased until the defined oil volume, representing the fixed bladder compression ratio, is moved.

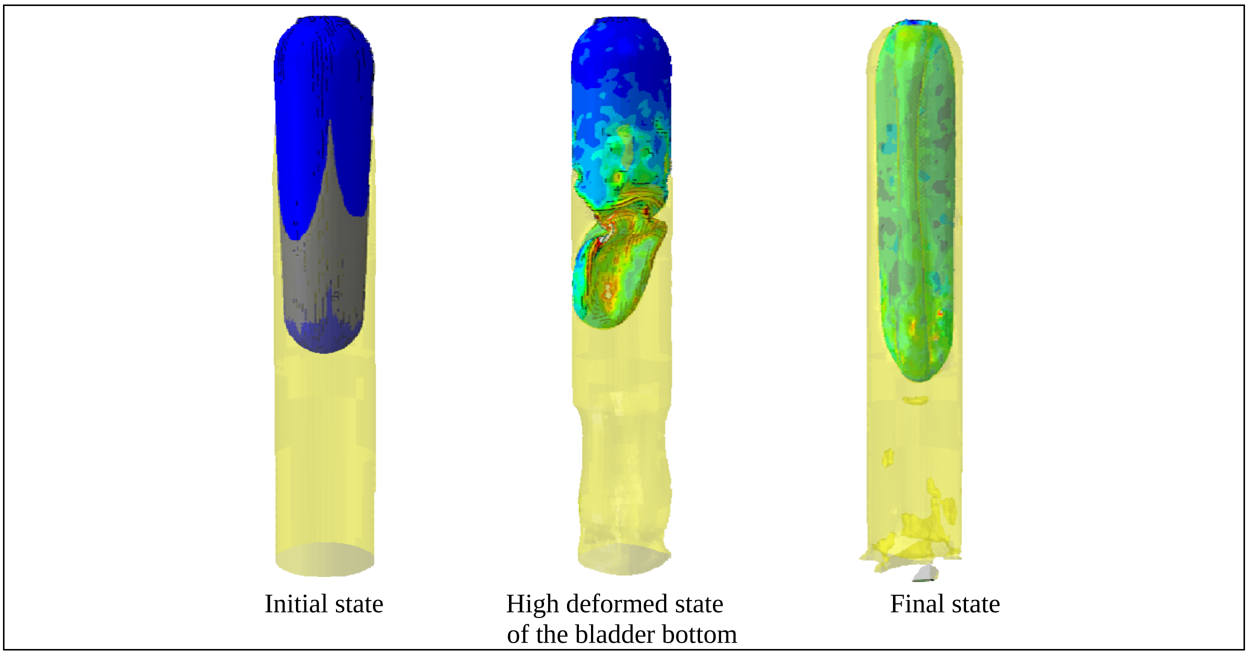


Figure 7. Multi-physic simulation of the accelerated test bench

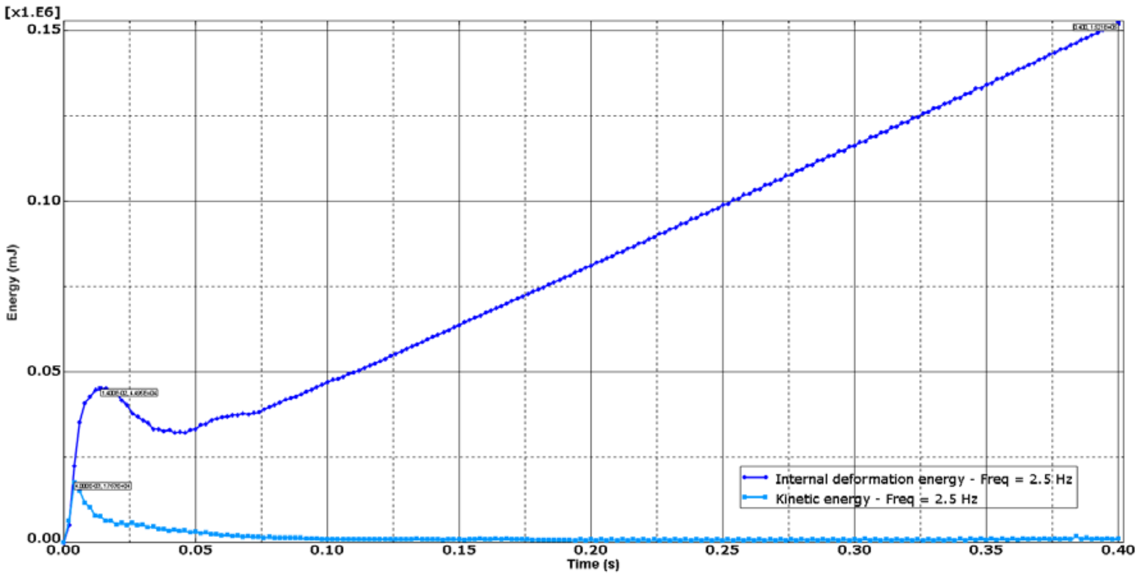


Figure 8. Evolution of the energy during the accelerated testing solicitation at 2.5 Hz

5 RESULTS

In the framework of the predictive reliability approach, other expected results from the modelling are the lifetime estimation and comparison of the severity level between the accelerated endurance test bench and the real application.

Using the bladder internal deformation energy, it is possible to estimate the lifetime ratio between the testing and the service conditions. The energy evolution during the rotation of the bladder in service is determined for both accumulators in the perpendicular and parallel position with rotation axis. The associated energy curves are presented respectively in Figures 4 and 5. These calculations correspond to a simulation of the first accumulator rotation at 30 rpm (one rotation in 2 seconds) for both perpendicular and parallel positions

The table 1 gives the maximal internal deformation energy obtained from the numerical results. According to the plotted curves, the internal deformation energy ratio between the perpendicular and the parallel is a conservative factor of 3. The average strain ratio is then calculated from the square root of the energy ratio.

The relation between strain and failure cycle number is given by the equation related to the fatigue curve. This latter has been calibrated on the basis of rubber material fatigue testing for confidence level of 50%, leading to:

$$\mathrm{Ln}(N) = -3\mathrm{Ln}(\varepsilon) + 12.98 \qquad (1)$$

Where, ε is the strain and N is the failure cycle number (lifetime).

From the relation (1), on may lead to the relation between lifetime and the strain ratios between service and the test:

$$\frac{N_S}{N_T} = \left(\frac{\varepsilon_T}{\varepsilon_S}\right)^3 \qquad (2)$$

Using this relation, the estimated MTBF ratios between the service and the test are given in the table 1, which seems to be consistent with the experimental results.
This is one of the post processing proposals that can be used which considers the square root of the internal deformation energy as the severity indicator of the solicitation applied to the bladder. Other severity indicators can be evaluated, such as: kinetic energy, maximal local strain or stress in the critical zones.

	Internal deformation energy (mJ)	Energy ratio (N_T/N_S)	Average strain ratio ($\varepsilon_T/\varepsilon_S$)	MTBF ratio (N_S/N_T)
Test	151286	-	-	-
In service perpendicular mode	18391	8.2	2.86	23
In service parallel mode	6130	24.7	4.97	125

Table 1- in service MTBF estimation in comparison to accelerated testing

6 CONCLUSION

This work has permitted to develop a new modelling of the accelerated endurance test bench using mult-physic approach. This approach using the CEL technique available in Abaqus FE code has conducted to simulate both the fluid domain and structure domain as well as their interaction, allowing to take into account the real loading produced by the fluid solid interaction.

The numerical results have shown clearly the predictive capability of this modelling for the representation of the real behaviour of the bladder in the accelerated endurance test bench:

- The deformation bladder stages is consistent with the testing observation
- The dynamic effect associated to the fluid movement is well reproduced by the modelling, showing the increase of the solicitation severity when the frequency is increased.
- The model has permitted also to give a degree of severity between the test bench and the service for both two position situations (perpendicular and parallel to rotation axis). The calculated MTBF ratios with 50 % of confidence level: 23 and 125 obtained for respectively the perpendicular and parallel positions are realistic. The testing is still in progress to confirm the tendency with more batches.

This modelling constitutes also an encouraging tool for the achievement of the proposed predictive reliability approach. The severity between the service and accelerated testing are consistent with the testing results.
In addition, the knowledge base which is derived from the methodology proposed brings a valuable help in development of both new bladder material and design.

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