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K. Förster / F. Mantwill / T. Brüger

Laboratory tests as a base for life time prediction of passenger car air springs

Introduction

In the 1960-ies air springs with rolling bellows were used in upper class passenger cars such as the Borgward P100 and Mercedes 600 (W100) for the first time. Before that this technology became a standard in the field of commercial transport vehicles (trains and trucks) and other industrial applications. However the passenger car air spring was not successful at this time, because of problems related to tightness, life time durability and costs.

In 1998 air springs re-introduced into the market with the Mercedes S-Class (Figure 1). Since then the application of air springs in the middle- and upper class cars has been growing continuously.

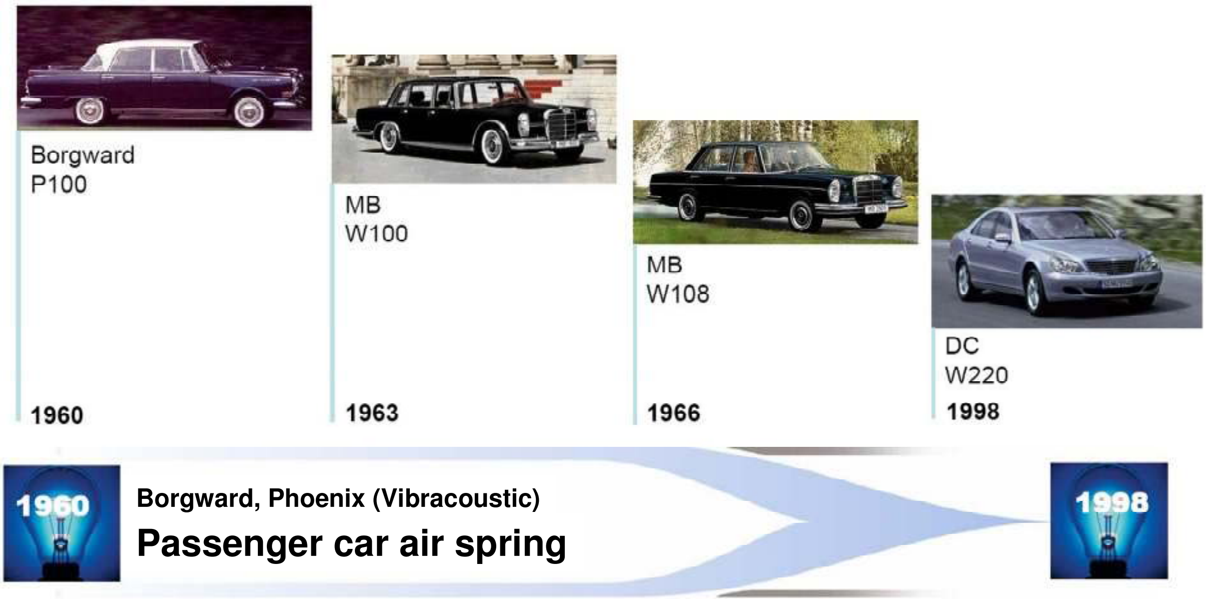

Figure 1: Application of passenger car air springs till 1998 [2]

Because of the challenging requirements regarding the driving comfort and the required package space, a knowledge transfer from air springs used in trucks to the field of passenger cars is quite difficult. Thus the knowledge base related to air springs for passenger cars is limited. At present, knowledge in this field has to be gained up by

extensive product experience and research. Especially for the lifetime prediction of passenger car air springs extensive knowledge and design tools are missing [3].
Furthermore, air springs are often integrated in a strut and therefore they have to be engineered and designed for each car individually. In addition functionalities of air struts, steering and controlling functions are permanently extended.
Therefore, a research project was agreed upon between Vibracoustic GmbH & Co. KG and the Helmut-Schmidt-University in Hamburg. The task of this project is to enlarge the knowledge in the field of lifetime prediction for air springs. In order to make this possible, precise conditions regarding the material properties, properties of the air spring components, especially the air bellow, as well as the knowledge about the occurring loads in cars are essential.
This paper describes the evaluation of the lifetime properties of air bellows.

Design of air springs for passenger cars

The key element of each air spring is the rolling bellow. By using clamping rings the bellow is mounted on an upper fitting and on a piston. Due to the pressurization of the bellow with $p_{Ü}$ a rolling fold will be formed. As pressure medium common air is used. Figure 2 shows the basic design cross section of an air spring with its typical components.
The spring force F_{LF} results of the pressure $p_{Ü}$ and the effective cross section surface A_{LF} of the air spring [4]. A spring deflection can be affected by the rolling fold rolls on a piston. Therefore the piston plunges into the air volume, which is enclosed by the bellow (Figure 2).
Especially for passenger cars the air spring needs to provide a high level driving comfort. Hence, the bellow wall thickness has to be reduced to a minimum. At the same time the bellow is the most stressed element of the spring. During the roll off, it changes its diameter from D_A to D_I. That's why high bellow elasticity is required. In contrast to the elasticity the bellow shall not stretch noticeably, when the pressure increases. This is important to avoid exceeding a given package space. So the bellow properties affect the properties of an air spring and its durability significantly.

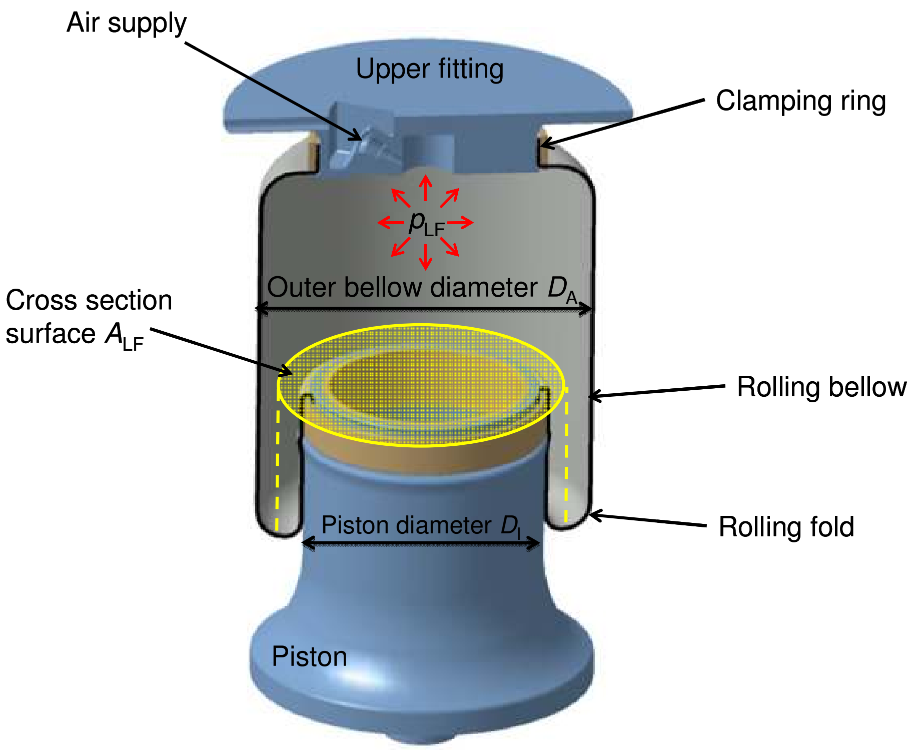

Figure 2: Design of passenger car air springs [1]

To fulfil the discussed requirements the bellow consists of elastomeric materials and is provided with embedded strength supporting plies. These supporting plies are made of polyamide or aramid threads. Figure 3 shows the two available bellow types and their design, which can be mounted in passenger car air springs. These types are the axial bellow and the cross ply bellow respectively.

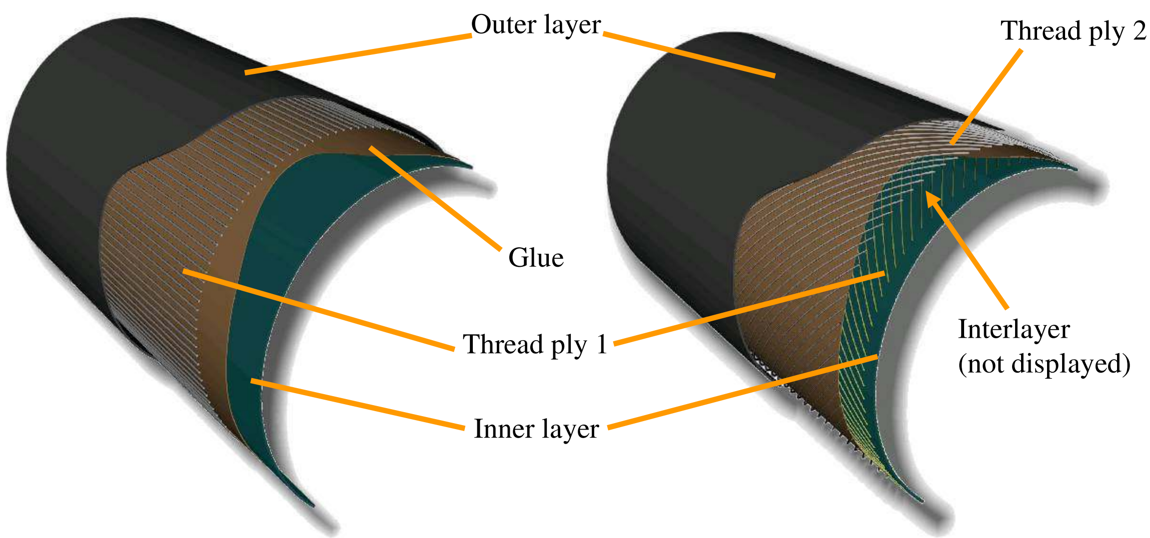

Figure 3: Design of axial bellow (left) and cross ply bellow (right) [2]

The axial bellow has only one thread ply, which is aligned in axial direction to the centreline of the bellow. Therefore a guiding tube is necessary. Its task is to absorb the resulting tangential forces, when the bellows will be pressurized with $p_{Ü}$. In contrast cross ply bellows have two thread plies, which are separated from each other by an interlayer. The inner layer avoids diffusion of the enclosed air while the outer layer protects the bellow from mechanical damages. The inner, outer and interlayer are made of elastomer.

The glue (Figure 3) ensures a best possible adhesion between the elastomeric matrix and the threads.

Concept for lifetime prediction for air springs

The tests made for the lifetime prediction have to be done under as constant laboratory conditions as possible in order to determine exactly the influences of selected parameters on the air spring durability. According to figure 3 the issued tests are parted in two groups: On the one hand determination tests of the operation parameters, on the other hand design and manufacturing parameters.

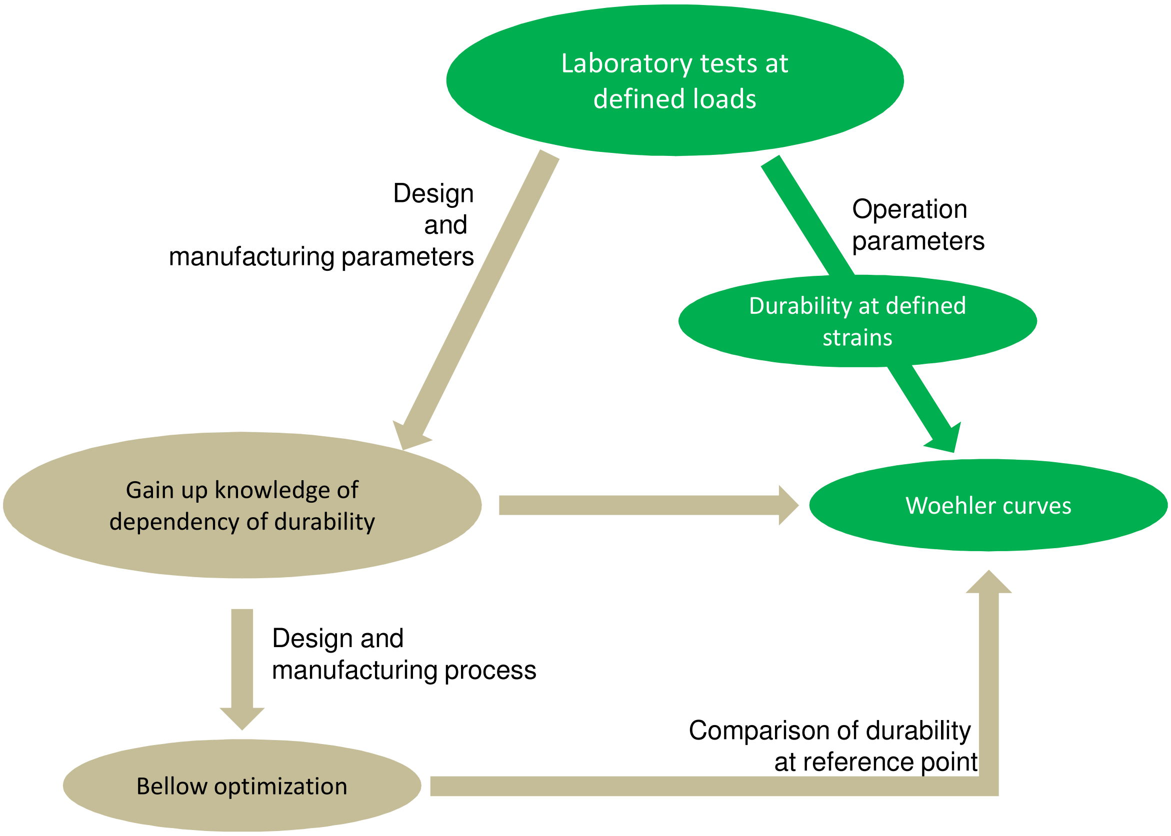

Figure 4: Fatigue tests at laboratory conditions

The tests regarding design and manufacturing parameters are made in order to optimise the durability of air spring bellows. Therefore the determination of corresponding parameters is calculated and evaluated quantitatively. That way, the design engineer gets technological aid which will lead to an optimisation of the assembly, based on the reference bellow.

Same is valid for the operation parameters, which can basically influence the durability of the bellow and therefore of an air spring. It is the objective to create Woehler curves for the analyzed bellow. These can be used for the optimisation of the air spring design as well as a reference for the bellow optimisation itself. At the same time, the tests for the determined endurances are a basis for the lifetime prediction of air springs. The interrelationship is shown in figure 4.

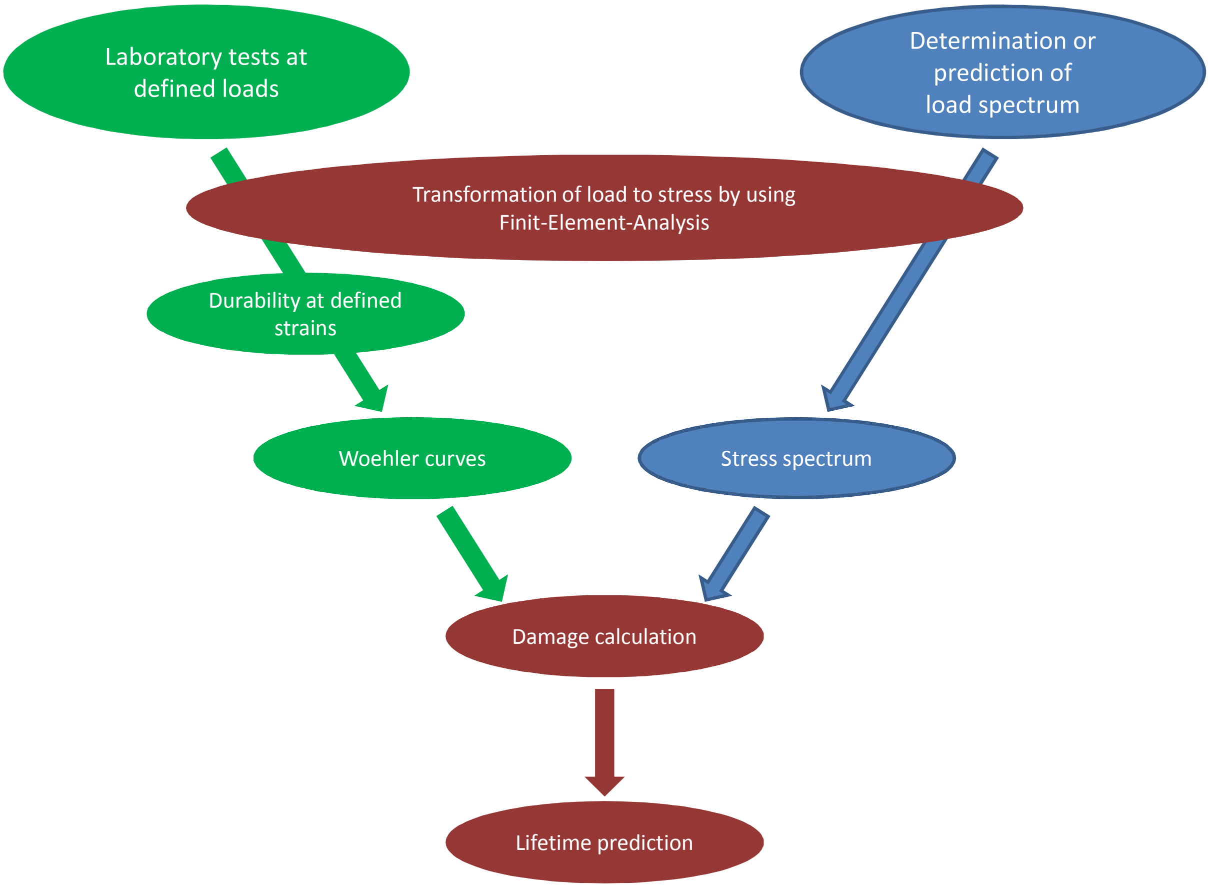

Figure 5: Concept of life time prediction for air springs [3]

According to this figure there are not only durability properties necessary for the lifetime prediction of air springs, but also load spectrums. These are taken in vehicle measurements and transferred into stress spectrums especially for the bellow. Therefore the Finite-Element-Analysis will be used. Here, the bellow load in the vehicle is compared – with the help of appropriate calculating models - with the demands and tests made in the laboratory. On this basis, later on it is possible to make a lifetime prediction for air springs via a fatigue life calculation.

Laboratory tests

Due to its design the cross ply bellow still has considerable development potential. However, only restricted knowledge is available concerning the influence of particular design and operating parameters on the bellow durability and harshness behavior. That's why the cross ply bellow will be subject of the described procedure. Of course the procedure is principally applicable for the axial bellow too.

Fatigue test runtime and damage mechanism

In order to obtain test results within a very short time, the duration of the fatigue tests has to be reduced to a minimum. This minimisation has limits, though. If results are to be achieved that are comparable to the failure of an air spring in a vehicle, one cannot arbitrarily increase the test speed. Due to the damping characteristics of the elastomer an improper heat dissipation in the bellow would be the consequence. Further on, this could lead to damages which would not occur on a real vehicle. This means that the damage mechanisms that occur in a real vehicle also have to lead to a failure of the air spring respectively the bellow within the laboratory tests.

The dominating damage mechanism that leads to the failure of an air spring in a vehicle is the passing of a stationary point on the bellow through the rolling fold (figure 6). The passing through the rolling fold causes a change of the angle α between the thread plies and thread distance a_F as well. This effects complex elastomer deformations in the bellow.

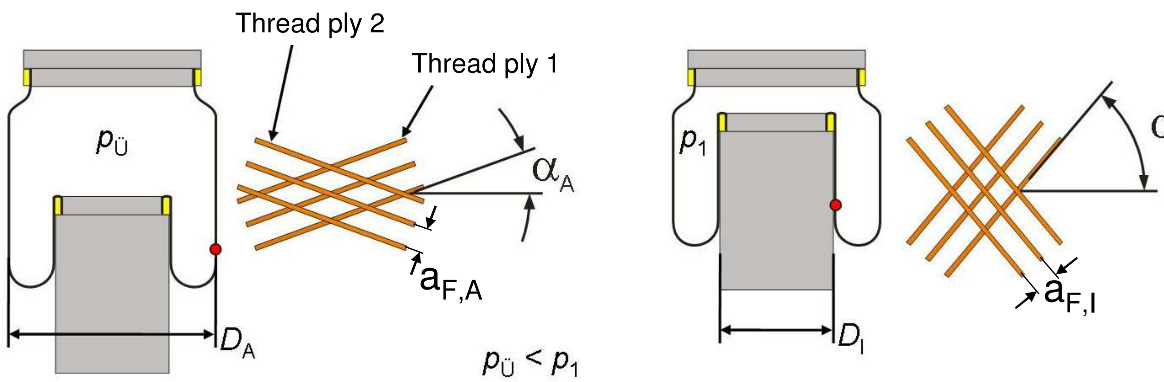

Figure 6: Change of thread angle and distance during passing the rolling fold [3]

Resulting spring force

Owing to the de- and inflection of a vehicle, the piston plunges into and out of the air volume enclosed by the bellow (Figure 6). This causes a change in the air spring pressure, which causes different spring forces $F_{LF}(t)$. This correlation is defined in the equation

$$F_{LF}(t) = p_{\ddot{U}}(t) A_{LF}(t).$$

Figure 7 shows an example of a quasi static load deflection curve of a passenger car air spring. A maximum load of 15 kN was measured, but at dynamic inflection the spring forced can be much higher. This is caused by the inertia of the bellow and the isentropic changes of conditions for the enclosed air volume. Thus, according to the high test speed, high performance requirements have to be met by the propulsion of a fatigue test rig.

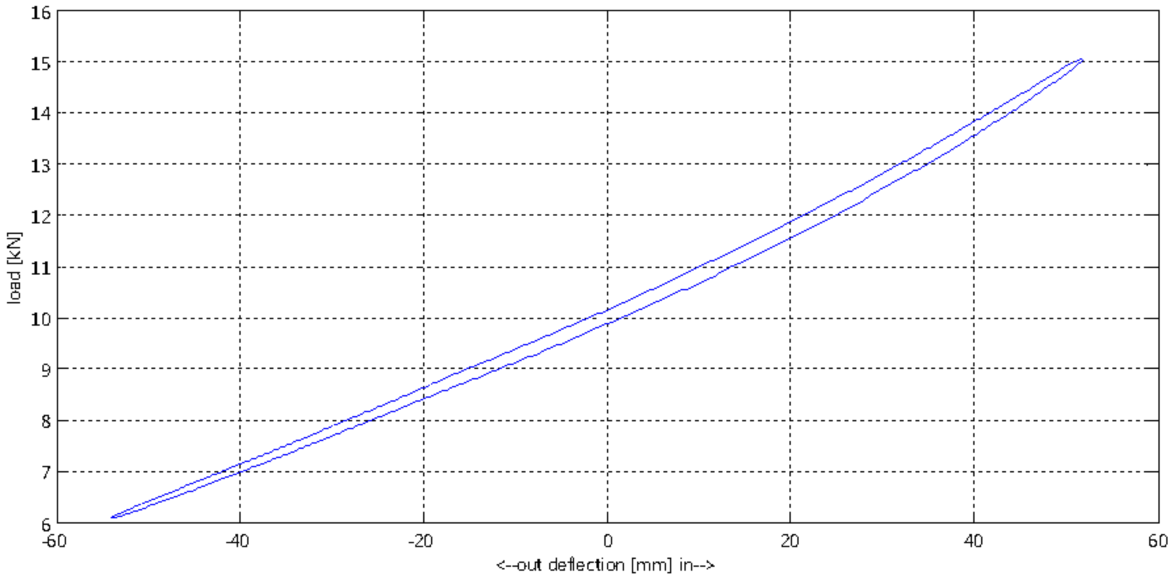

Figure 7: Example for a static characteristic curve of an air spring

Alternative fatigue test for air spring bellows

In order to eliminate the resulting spring forces during the laboratory tests, an alternative fatigue test according to [5] was conceived. Accordingly, the air spring bellow is mounted on two pistons (Figure 8). This causes two rolling folds as soon as the bellow gets stressed by a pressure. A bracket supports the bellow in the load frame. Due to the fact that the rolling folds are situated opposite each other, there are no resulting spring forces that strain the propulsion. Additionally, pressure fluctuations are avoided because the enclosed air volume remains stable due to the cylindrical pistons.

Thus rather a high test speed is possible. The test rig shown on the right side in figure 8 can be operated with a test frequency of 10.5 Hz while performing an amplitude of up to $\hat{s} = \pm 42 \ mm$. Preliminary tests have proven that the high test speed does not influence the damage mechanism of the air spring bellows. The bellows that failed in the alternative test do not show any difference to the failure of real air springs. This means a rather strong increase of the possible test speed, compared to fatigue tests with complete air springs. There, test frequencies amounts up to 1.6…3.2 Hz [3].

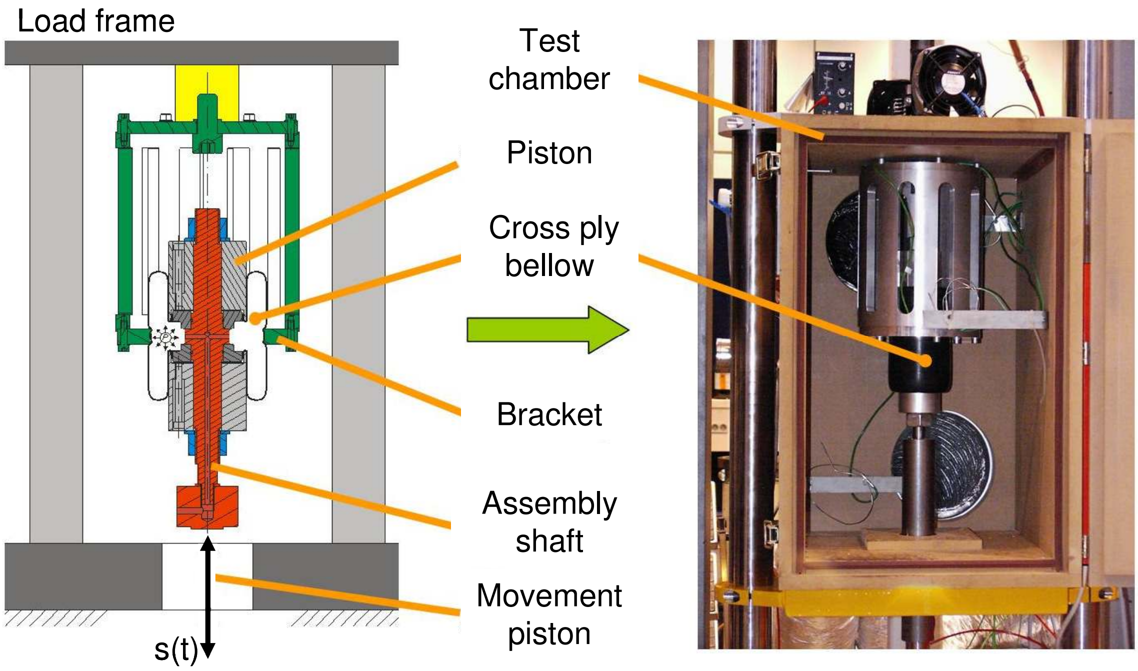

Figure 8: Functional principle of the alternative fatigue test for air spring bellows [3]

The pistons are driven with an amplitude $\hat{s}$ which ensures that a stationary point on the bellow completely passes through the rolling fold. Thus the damage mechanism described in part 5.1 is reproduced on this test rig.

At the same time the likelihood of failure of the bellow rises due to the simultaneous testing of two rolling folds.

Additionally to the design and manufacturing parameters, also the influence of the operating parameters on the bellow durability can be systematically determined because of the stable pressure. These parameters are the pressure, the geometrical measurements of the rolling fold and the surrounding temperature.

Furthermore, with a suiting force transducer the harshness of a bellow can be determined. The harshness describes the deformation resistance of the bellow when rolling over the piston. It can have a significant influence on the driving comfort and thus should not be disregarded in this context. Moreover, the losses of a bellow can be determined and conclusions can be drawn regarding the internal heat dissipation.

Design of Experiments

As already mentioned, the air spring bellow consists of several components, which posses different physical properties. In terms of the failure characteristics they differ as well. In combination of the materials new damage patters appear beside the well known patters of the individual components. Such patters can be the delamination due to the insufficient adhesion between the elastomer and the reinforcing material or because of the significant gradient of stiffness inside the bellow.

In consideration of these complex coherencies a high number of reruns for every test point are needed, if the achieved durability shall be linked to the considered test parameters.

Regarding their influence on the bellow durability the operating parameters and the design and manufacturing parameters shall be determined. That's why different bellows need to be designed and produced. But the complexity of the bellow manufacturing represents a further problem, if for example the thread distance or the thickness of individual elastomer layers shall be varied.

In this case a systematic definition of experimental designs is necessary to provide a high expressiveness and statistic validation of the tests. Therefore methods of the Design of Experiments (DoE) will be used to plan and analyze the fatigue tests.

The experimental designs are images of the experiment space, which is restricted by the test parameters. A common used design is the 2^K-Design to evaluate linear dependencies between the test result and test parameters. More experiment designs and their basics of definition are described in [7].

The statistic analysis follows the fatigue tests. Subject of the analysis is the determination of regression models. Such models describe the dependence of a test result Y to X_K test parameters. A linear regression corresponds to the equation

$$Y = \beta_0 + \beta_1 X_1 + ... + \beta_K X_K .$$

Here the factor β_0 considers random errors of the test results. β_1 till β_K are estimators which numeralize the influence of parameters to the test result [7]. Later on the regression model provides an estimation of the bellow durability depending on any combination of determined test parameters of the experiment space. In addition to the linear regression model models of higher order can be estimated too.

The application of the explained procedure for laboratory tests is shown in Figure 9.

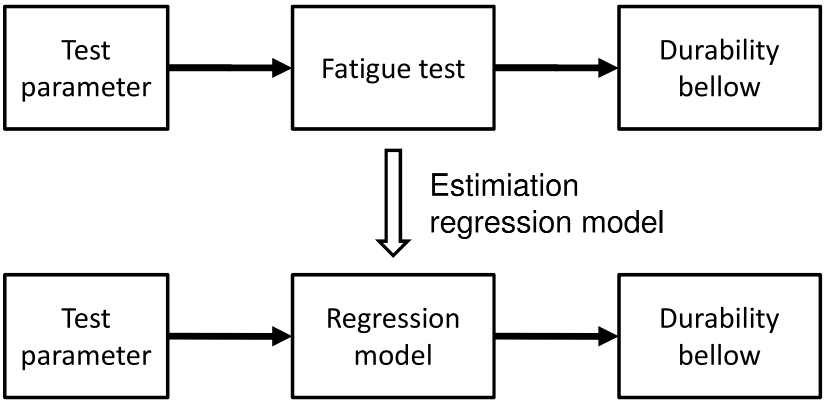

Figure 9: Connection between test parameters and test result

Fatigue tests and their analysis

In this section the influence of the operating parameters on the bellow durability will be determined. The regarded parameters are the piston diameter D_I, the pressure $p_{Ü}$ and the temperature ϑ. Figure 10 shows the defined experiment space. The fatigue tests will be accomplished with a cross ply bellow according to the explained design above.
To improve the quality and to reduce the struggling of the regression, the experiment space was expanded with additional points. The determined parameter sets are marked in Figure 10.

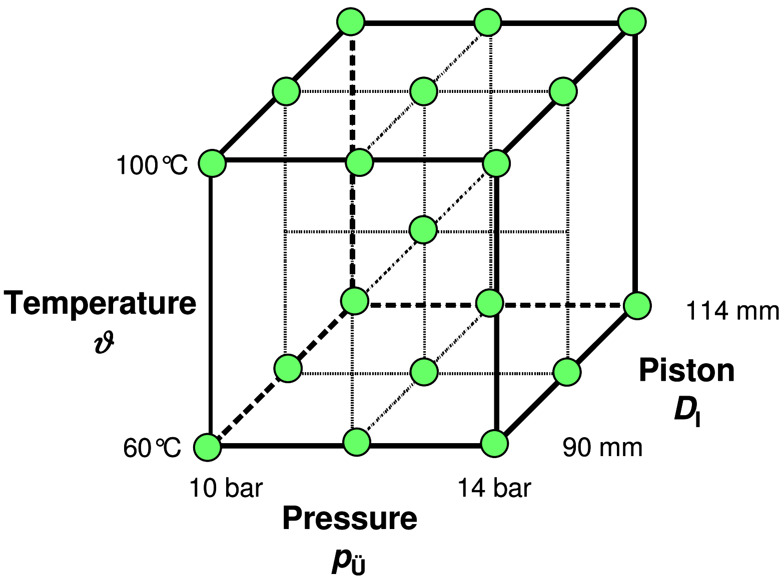

Figure 10: Experiment space for determination of the operating parameters

Regarding the straggling a linear regression will not describe the determined coherency sufficiently. That's why a quadratic regression was estimated, which regards interaction between the parameters to. The built model corresponds to the equation

$$LW = \beta_0 + \beta_1 D_I + \beta_2 p_{\ddot{U}} + \beta_3 \vartheta + \beta_4 D_I p_{\ddot{U}} + \beta_5 D_I \vartheta + \beta_6 p_{\ddot{U}} \vartheta + \beta_7 D_I^2 + \beta_8 p_{\ddot{U}}^2 + \beta_9 \vartheta^2 .$$

The factors β_0 till β_9 were estimated by using the software 'R'. This open source software was developed regarding the special requirements of solving statistic problems [8]. The diagrams in Figure 11 till Figure 13 show the estimated regression.

The dependence of the bellow durability on D_I and $p_{\ddot{U}}$ at a temperature of up to 60 °C is shown in Figure 11. The durability depends significantly on the pressure. For example the number of Load cycles grows with a factor of 11.5 from 240.00 LC up to 2.750.000 LC, if the pressure sinks from 13 bar to 10 bar. The numbers are valid for a piston diameter of about 90 mm.

At an adequate number of load cycles it appears that the piston diameter has an influence on the durability. At a pressure of 10 bar the number of load cycles grows from 2.750.000 LC ($D_I = 90\ mm$) up to 2.800.000 LC ($D_I = 94\ mm$). Afterwards, the durability falls to 1.700.000 LC ($D_I = 114\ mm$). This observation is similar to the dependency of the mean load of natural rubber [6]. However, at 12 bar and 14 bar this dependency is imperceptible. It is possible, that the bellow durability will be dominated by $p_{\ddot{U}}$ at a higher pressure levels.

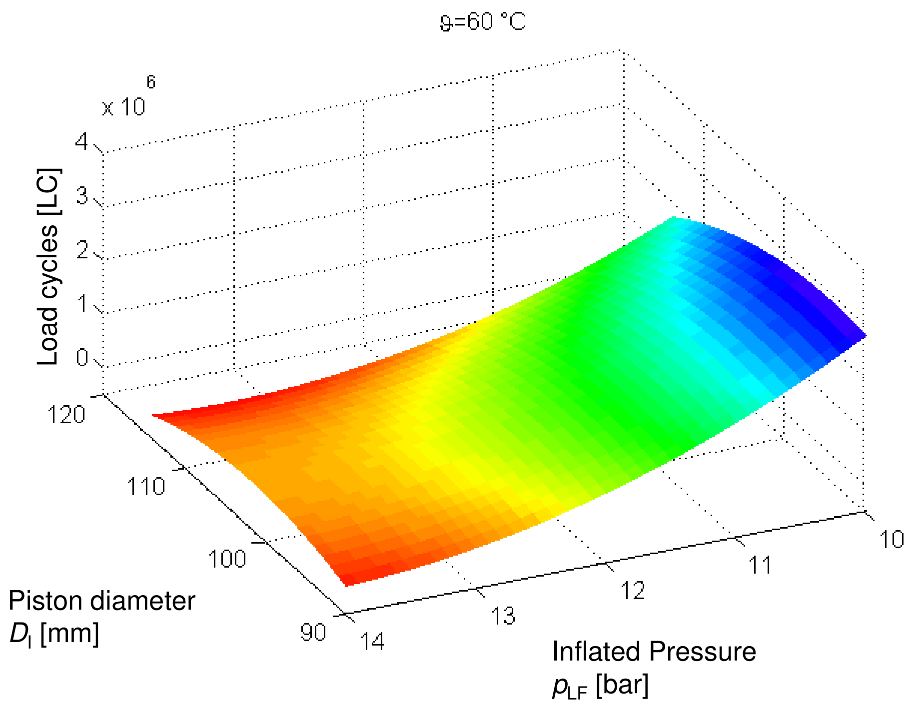

Figure 11: Bellow's durability depending on piston diameter and inflated pressure

In contrast the influence of the temperature on the bellow durability is lower than the influence of $p_{Ü}$ (Figure 12). Though, the number of load cycles grows with a factor of 1.4, if the temperature falls from 100 °C down to 60 °C. Here, the piston diameter is 90 mm.

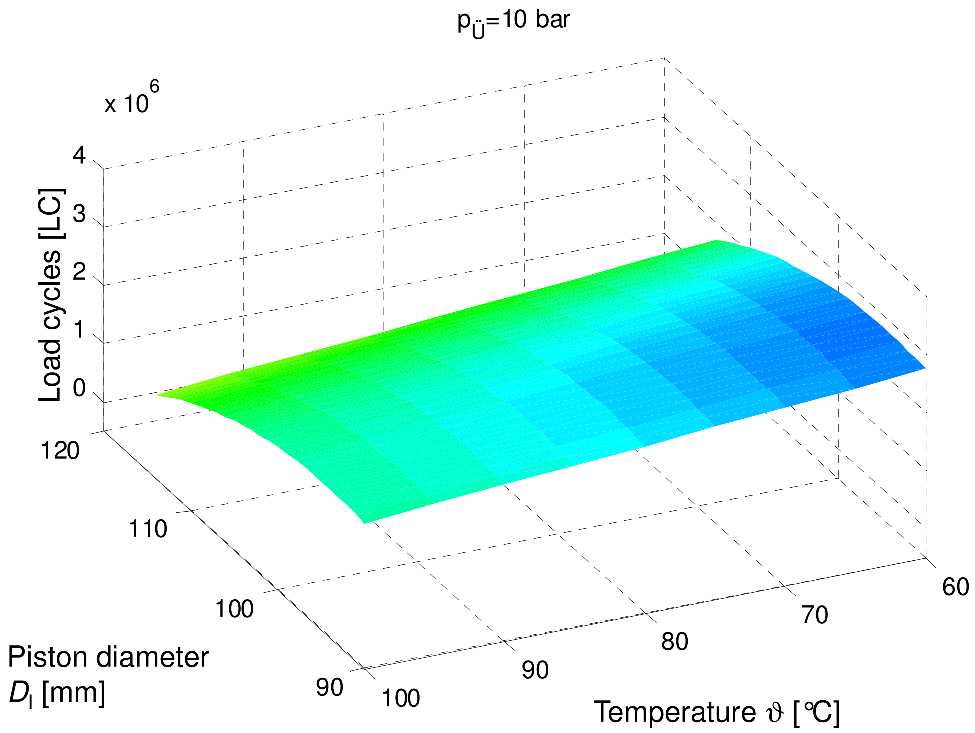

Figure 12: Bellow's durability depending on piston diameter and temperature

Referring to the maximum achieved lifetime, the straggling of the model amounts up to 11.2 %. This is still the weakness of the estimated model. Because of the straggling, negative numbers of load cycles can be calculated, if pressure and pistons diameter exceed a limit (Figure 13). That does not correspond to reality.

A limitation of the scope of validity or a different model approach is a possibility to minimize the straggling and to improve the quality of the regression model. Therefore the enlargement of the experiment design is suggestive.

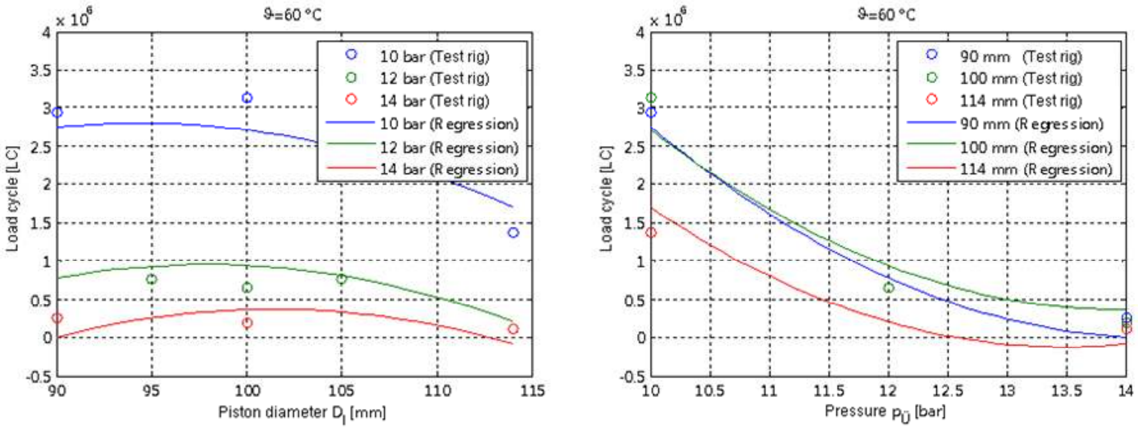

Figure 13: Comparison of regression and test results

Abstract and perspective

A fatigue test procedure was presented, which enables to determine necessary basics for the lifetime prediction of air springs. Subject of the laboratory tests is the determination of Woehler curves for air spring bellows. The bellow is the key element of an air spring, where complex distortions occur. They have a significant influence on its durability properties and had not been determined sufficiently until now.

At constant test conditions the presented fatigue test enables to determine the influence of operating, design and manufacturing parameters on the bellow durability.

The estimated regression model, which describes the dependency of the durability on operating parameters, is not sufficiently accurate. This problem needs to be solved, when the model should be used to implement a life fatigue calculation for air springs.

To optimize the durability and harshness properties of a bellow, their dependency on design and manufacturing parameters must be evaluated to. Therefore the number of interesting parameters has to be limited because of the diversity of possible fatigue tests.

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