Parametric sensitivity and optimization of washer bellows

Marcel Schmidt

Whirlpool Corporation

Poprad, Slovakia

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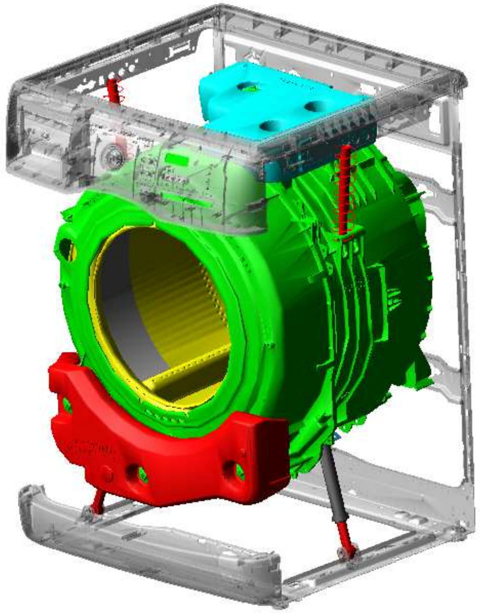
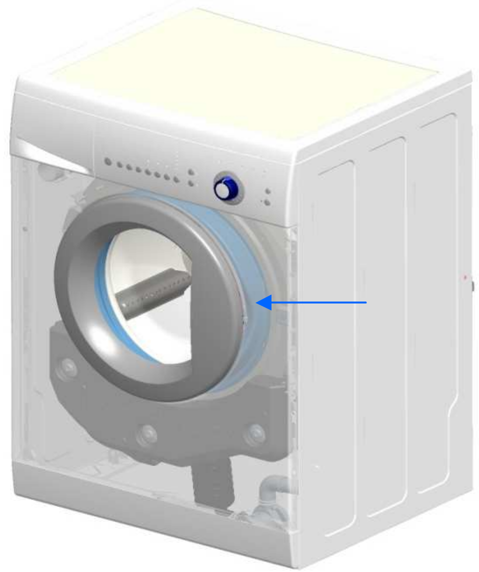
Topics

- *Bellow part explanation*
  - Objectives of development
  - Simulation approach
  - Correlation with test
- *Optislang*
  - DOE study — finding important parameters
  - Optimization — based on DOE
  - Robustness study of proposed part after optimization
- *Conclusion*

Bellow part explanation

- There are vertical and horizontal axis washing machines on consumer market available
- This work consider bellow calculations of horizontal axis machines front loaders
- Bellow connects moving washing unit (*tub + drum*) and stable door opening (*insert*)
- Bellow works as sealing against water and steam inside drum during wash cycle
- In addition front loader bellow keeps clothing contained inside the drum during wash cycle. If this bellows assembly were not used, small articles of clothing such as socks could slip out of the wash basket, and fall down the narrow slot between the tub and cabinet.
- Washers for the consumer market usually use a folded flexible bellows assembly around the door opening which is made of elastic material most commonly of rubber (EPDM)





Objectives of bellow developing

- Main objectives at developing: keeping transmitted forces as low as possible, decreasing of noise, guaranteed sealing (*wearing out quality*) properties for whole lifetime of washer (*durability*)

- Performed calculations focused on transmitted forces and wearing out quality

- Transmitted forces from washing unit to cabinet washer impact stability of washer – "*walking performance*" and also transmit vibrations to cabinet

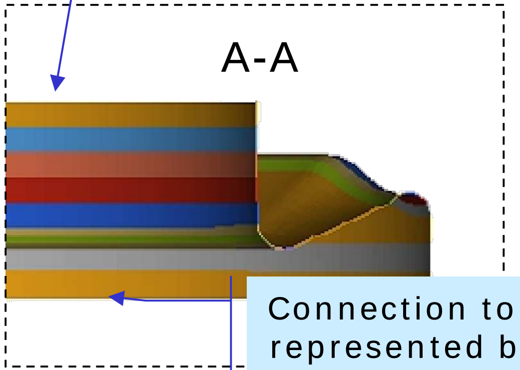
- No wearing out during lifetime
  - Abrasion caused by self-contact inside bellow can lead to wearing out of bellow and consequently to holes through which water and steam can leak out

Examples of abrasion at the end of lifetime of washer, picture made at development test, on serial washer bellow is <u>not allowed</u>

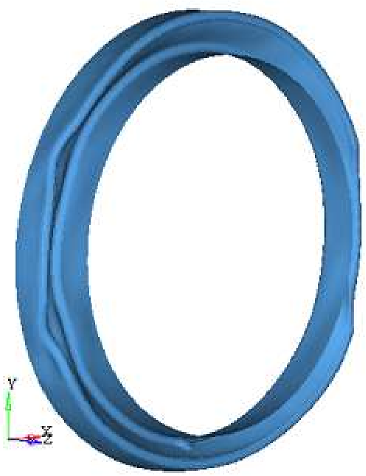
Simulation approach

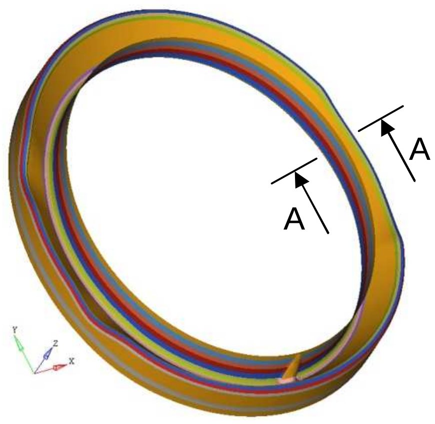
- Calculations of bellow have to be done as dynamic calculation because of high frequency movement of tub. Movements of tub are same as rotational speed of drum. Amplitudes of this movement are depended of distribution of laundry and its unbalance inside drum.
- Calculation of working range frequencies (300rpm-1200rpm).
- Because of dynamic behavior explicit approach is required

Connection to cabinet

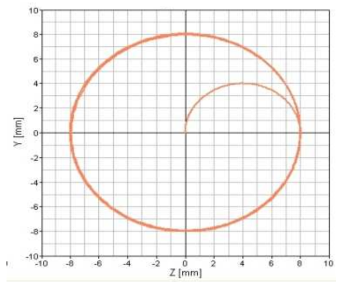


Connection to tub represented by prescribed motion, data sources are theoretical calculation, MB simulation, lab measurement



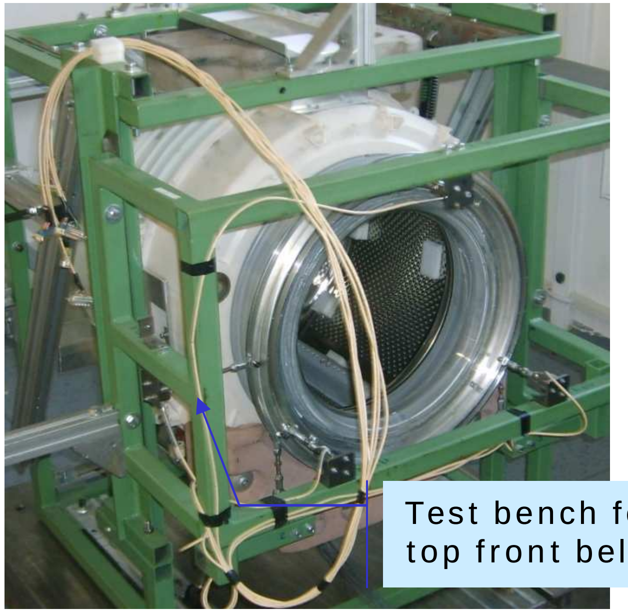


Tub movement

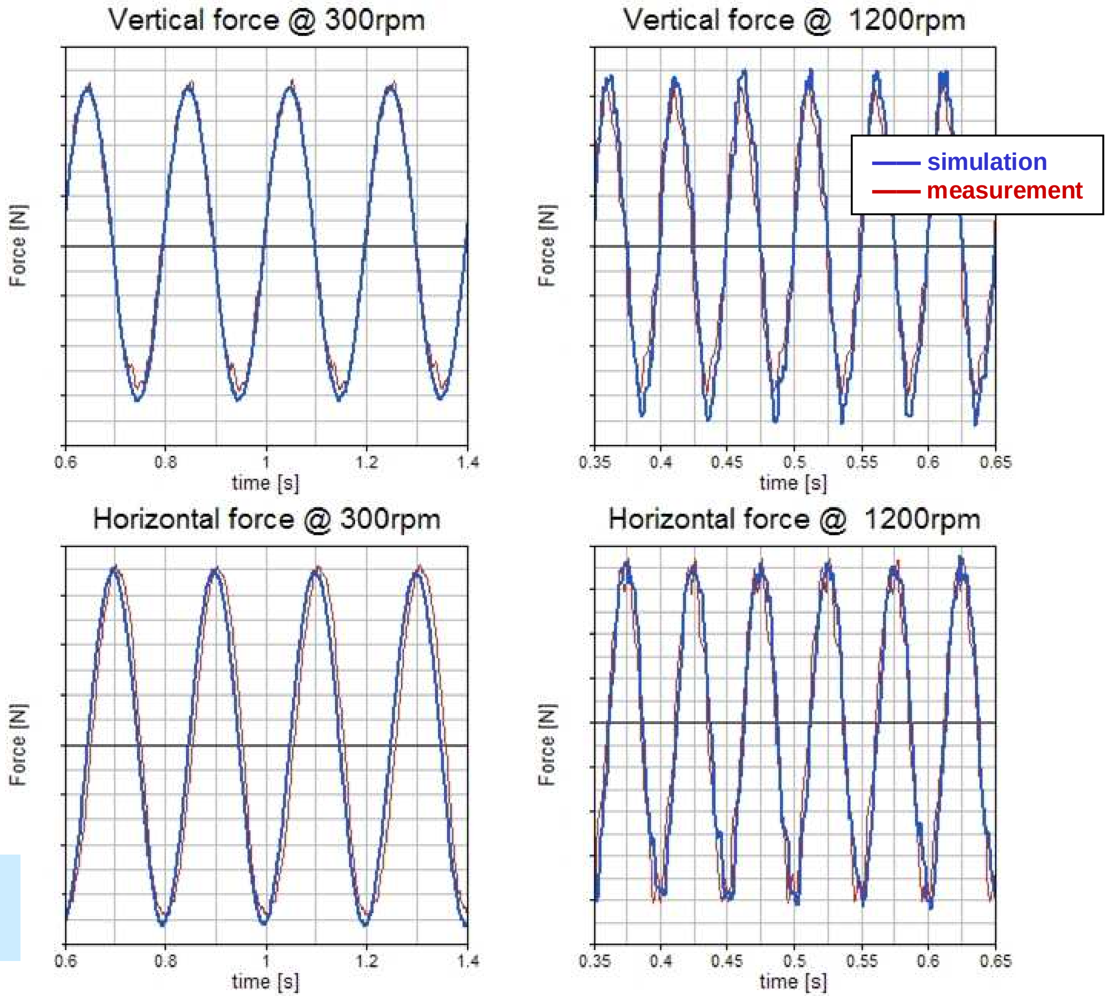


Front loader bellow test bench

- Output transmitted force and tub movement
- Set up of test bench for different load cases (*unbalance and distributed load*)
- Comparison of moving bellow by high speed camera



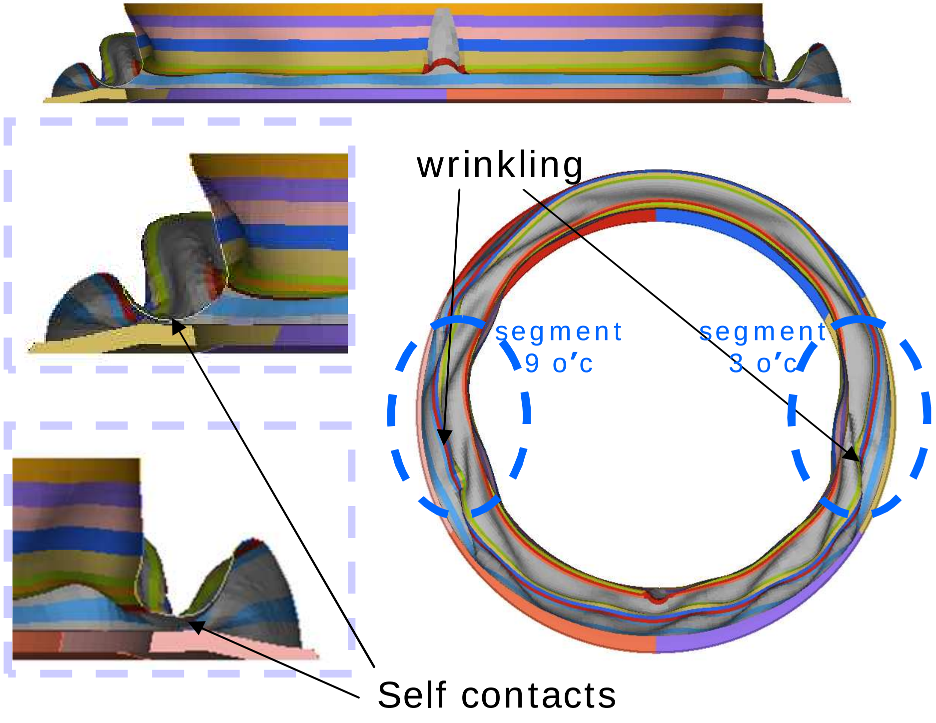
Test bench for top front bellow



Wear out of bellow

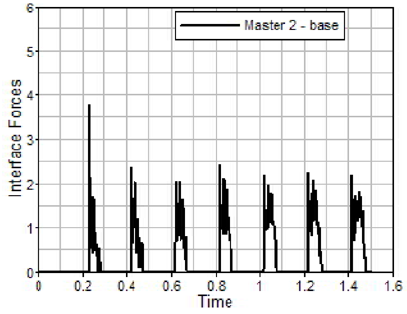
- High weights of laundry inside drum cause shift relative position between tub and door opening. This causes stretching of bellow
- By rotation around shifted position of frontal part of bellow (*fixation to door opening*) relatively to rear (*fixation to tub*) can occur undesirable self contact, which can cause wear out of bellow (*leak out*)
- Therefore by calculating of self contact forces we predict wear out of bellow

Situation with 1kg unbalance + DL:

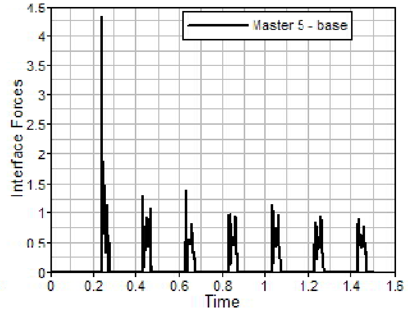


Self contacts at 300rpm

Segment 3o'clock

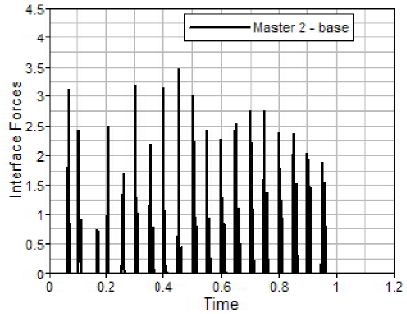


Segment 9o'clock

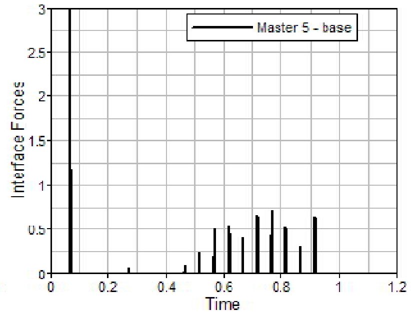


Self contacts at 1200rpm

Segment 3o'clock

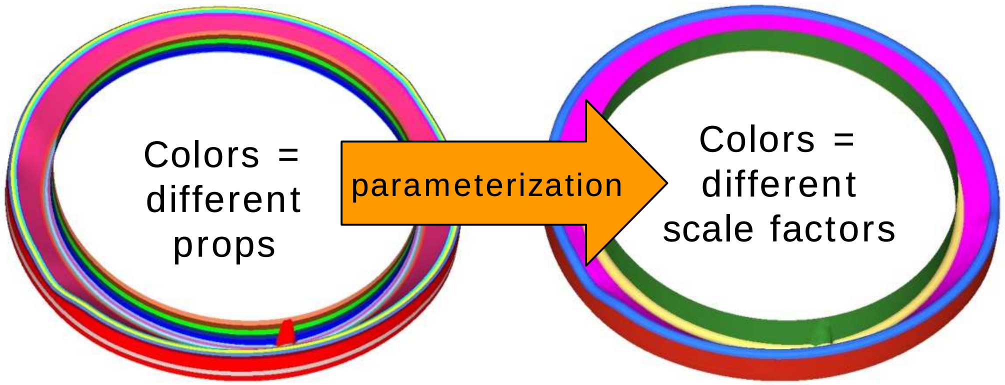


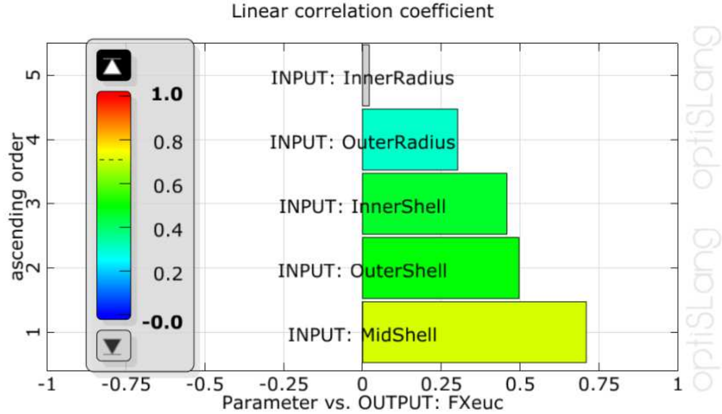
Segment 9o'clock



DOE— LC 1kg unbalance (front loader)

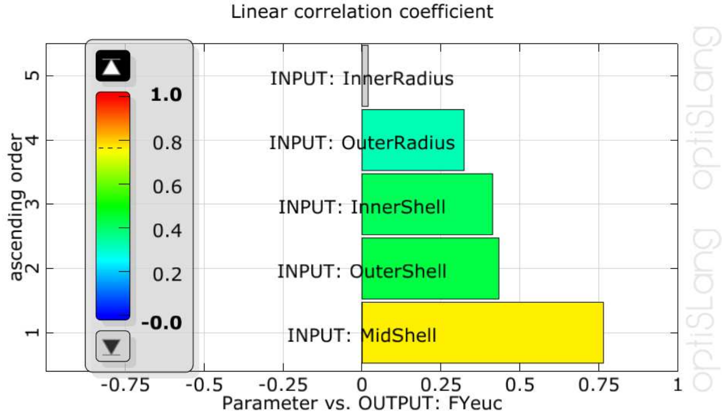
- DOE — 70 designs, 5 parameters
- Load case 1kg unbalance without distributed load inside drum — rotation axis without vertical shifting





- Parameterization: Bellow divided into 5 groups. For each group properties scaled by scale factor.

InnerShell
MidShell
OuterShell
InnerRadius
OuterRadius



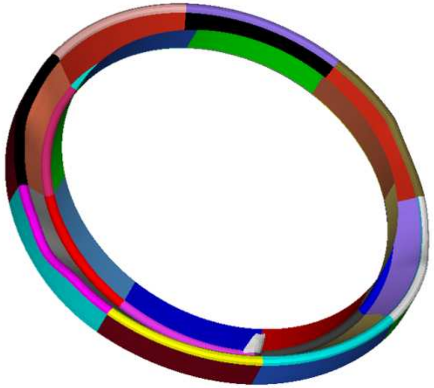
- Most important parameters are *shell, less important radiuses (Radiuses are stiff in this range of scale)
- All parameters are directly proportional to transmitted forces (linear correlation coefficients)
- In all 70 designs no self contact occurred — we can select lowest shell thicknesses for this load case to decrease transmitted forces

DOE — LC 1kg unbalance + distributed load

- Latin hypercube 200 designs, 40 parameters
- Shell thicknesses scaled through over all bellow
- Bellow divided through cut into 5 segments (*OuterShell, OuterRadius, MidShell, InnerRadius, InnerShell*)

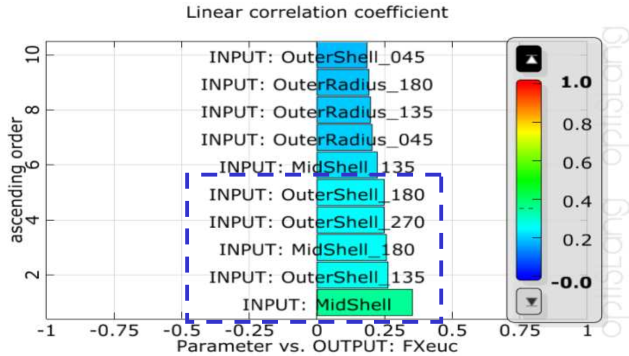
  and around bellow into 8 segments (*_XXX Degrees*)
- Number of segments 5x8

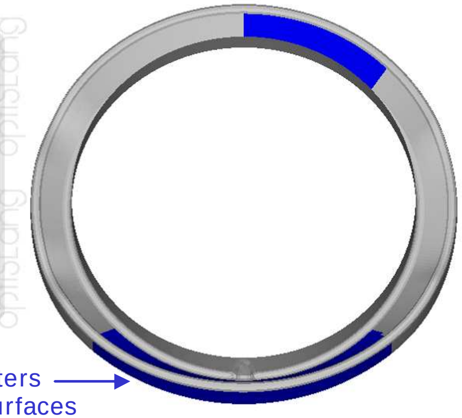
  =40 parameters
- Goal: Find sensitive parameters for transmitted forces and contact forces



Bellow divided into 40 surfaces, each thickness surface scaled separately = 40 parameters

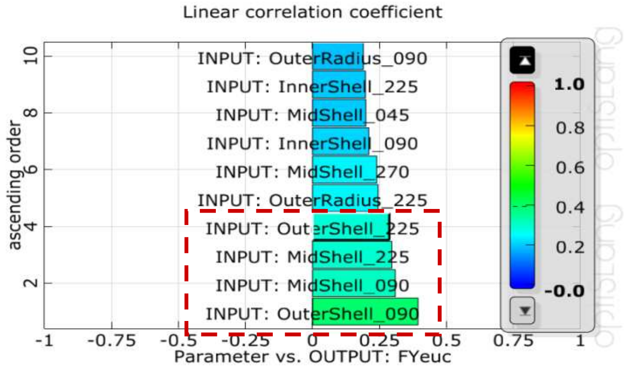
Vertical force — most important parameters

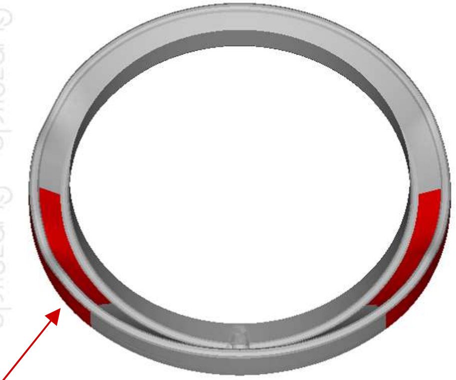




most important parameters were scale factors for surfaces

Horizontal force — most important parameters

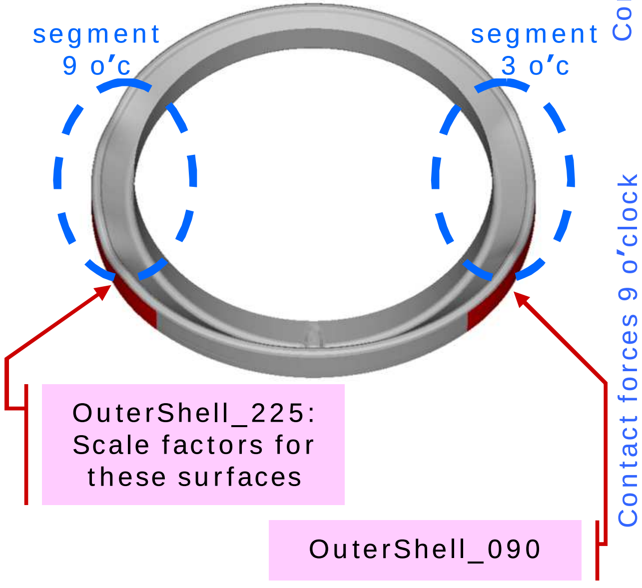


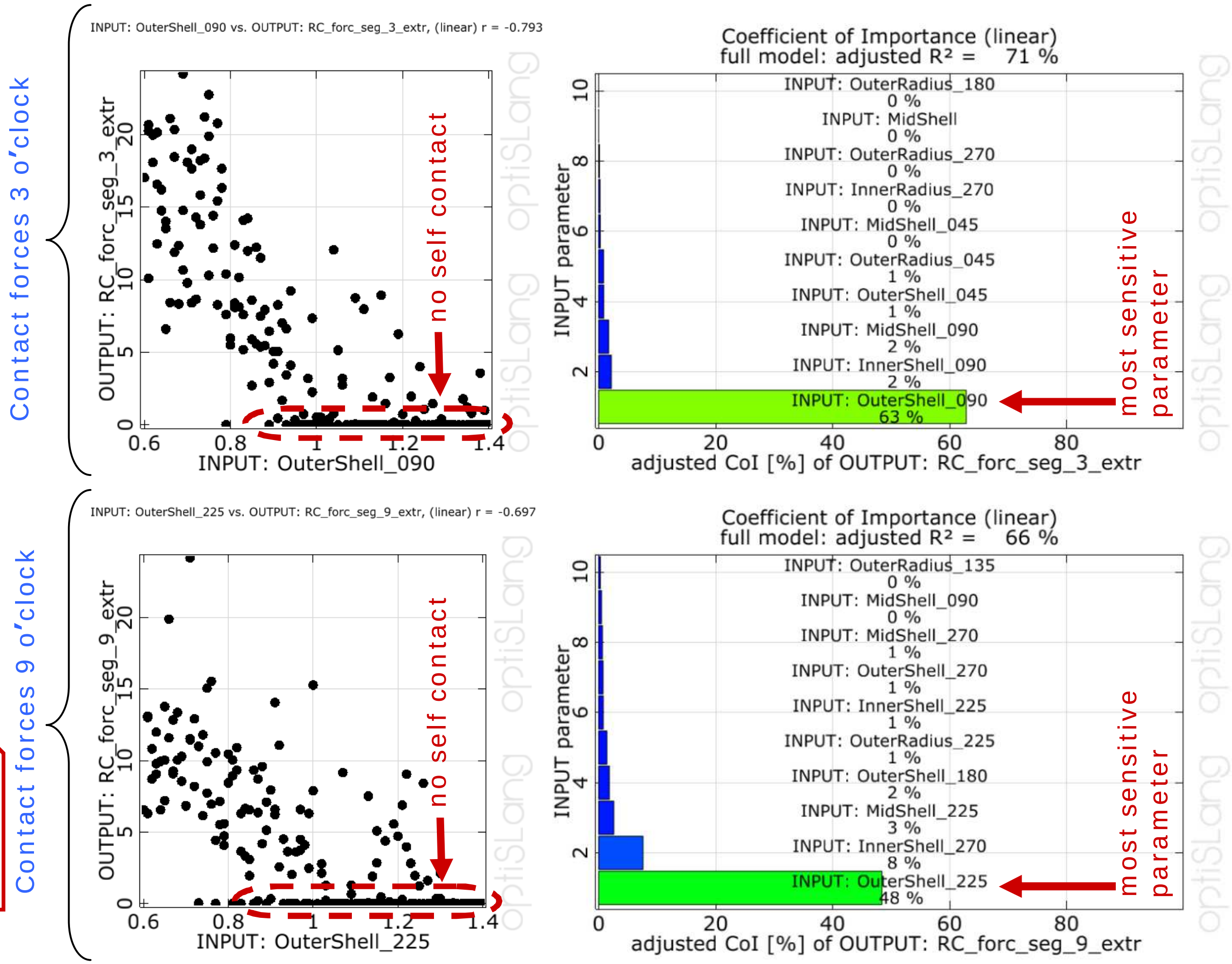


most important parameters were scale factors for surfaces

DOE — LC 1kg unbalance + distributed load

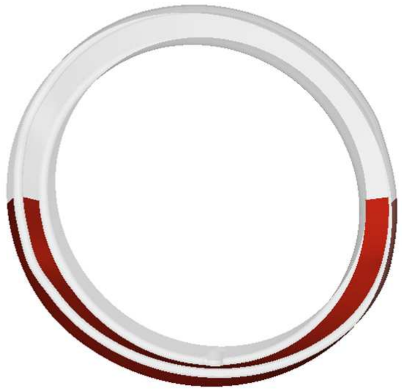
- This load case cause shifting of front and rear part of bellow
- Therefore self contacts can occur
- Desirable runs without self contact
- Most sensitive parameters OuterShell_225 and _090 (red surface on picture)



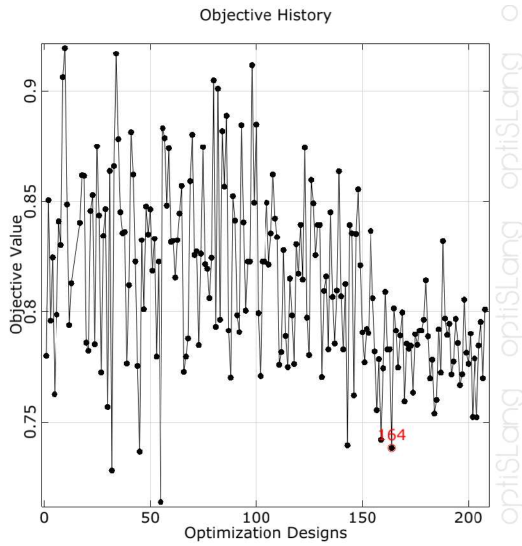


Optimization — Genetic algorithm

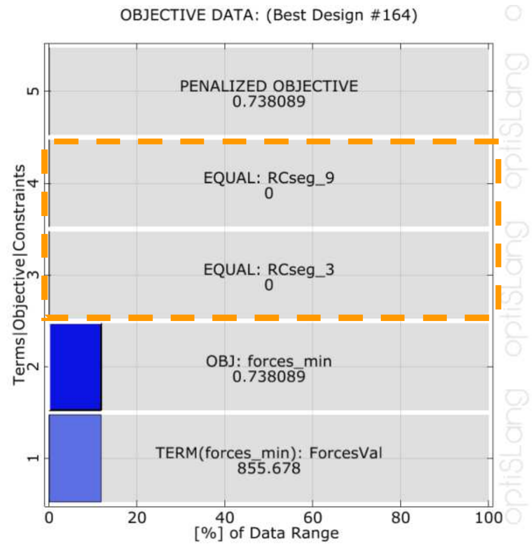
- Genetic algorithm
  - Load case 1kg unbalance + DL
  - Parameters were most important parameters found in DOEs (8 parameters)
  - The other unimportant parameters found in DOE set up on lowest manufacturable thickness (because of low transmitted forces and material cost)
  - Objective function = Horizontal force + Vertical force
  - Constrains: Contact forces = 0
  - Population size 16
  - Number of generations 13
- Total designs = 208



As parameters used scale factors for these surfaces (8 parameters)



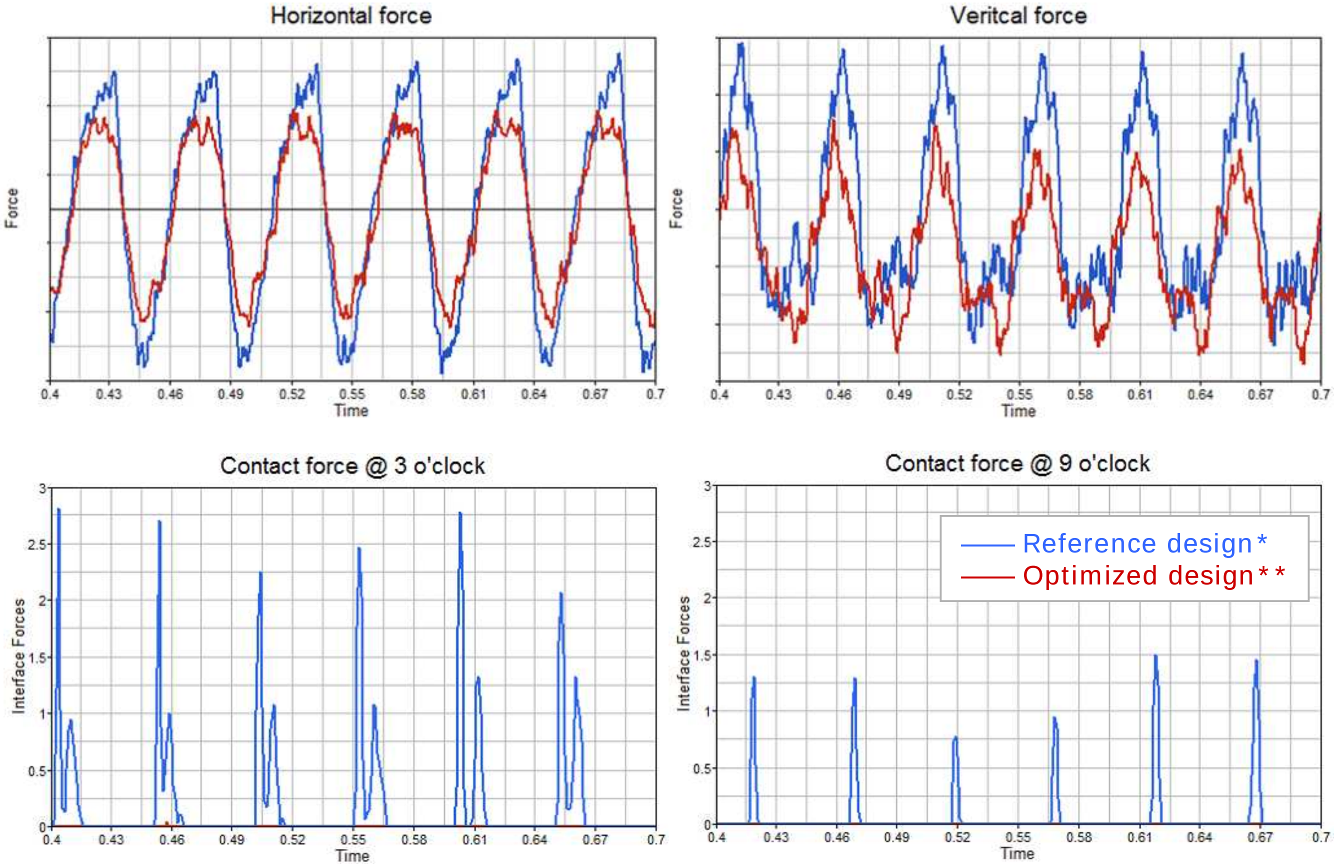
Objective history
Best design: 164



Objective data for design 164:
Constrains = 0

Summary optimization

- Result after raising knowledge from DOEs and running optimization using optiSLang
- Horizontal force decreased by ca. 31%
- Vertical force decreased by ca. 22%
- Eliminated contact forces
- Such bellow would transmit lower forces to cabinet (*lower vibration and noise*) and it's durability is much higher



- Such a design with few other modifications approved to production — "Optimized design for production"

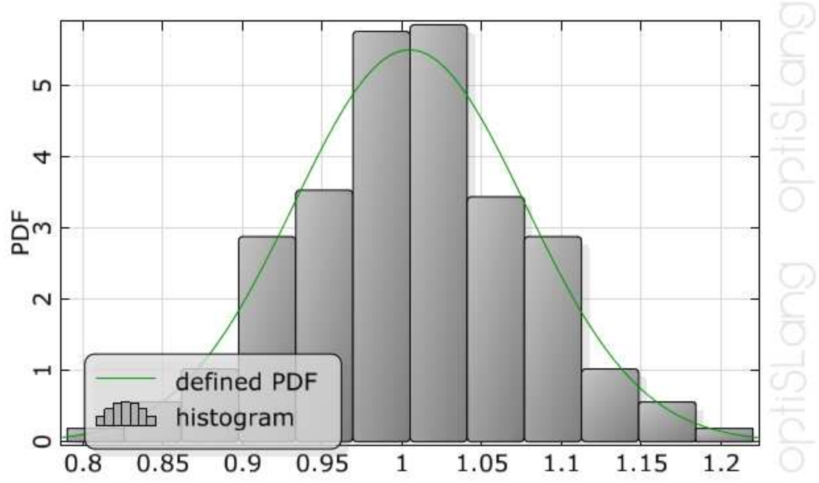
* Reference design before DOE and Optimization
** Best design (164) in genetic optimization

Robustness study

"Optimized design for production"

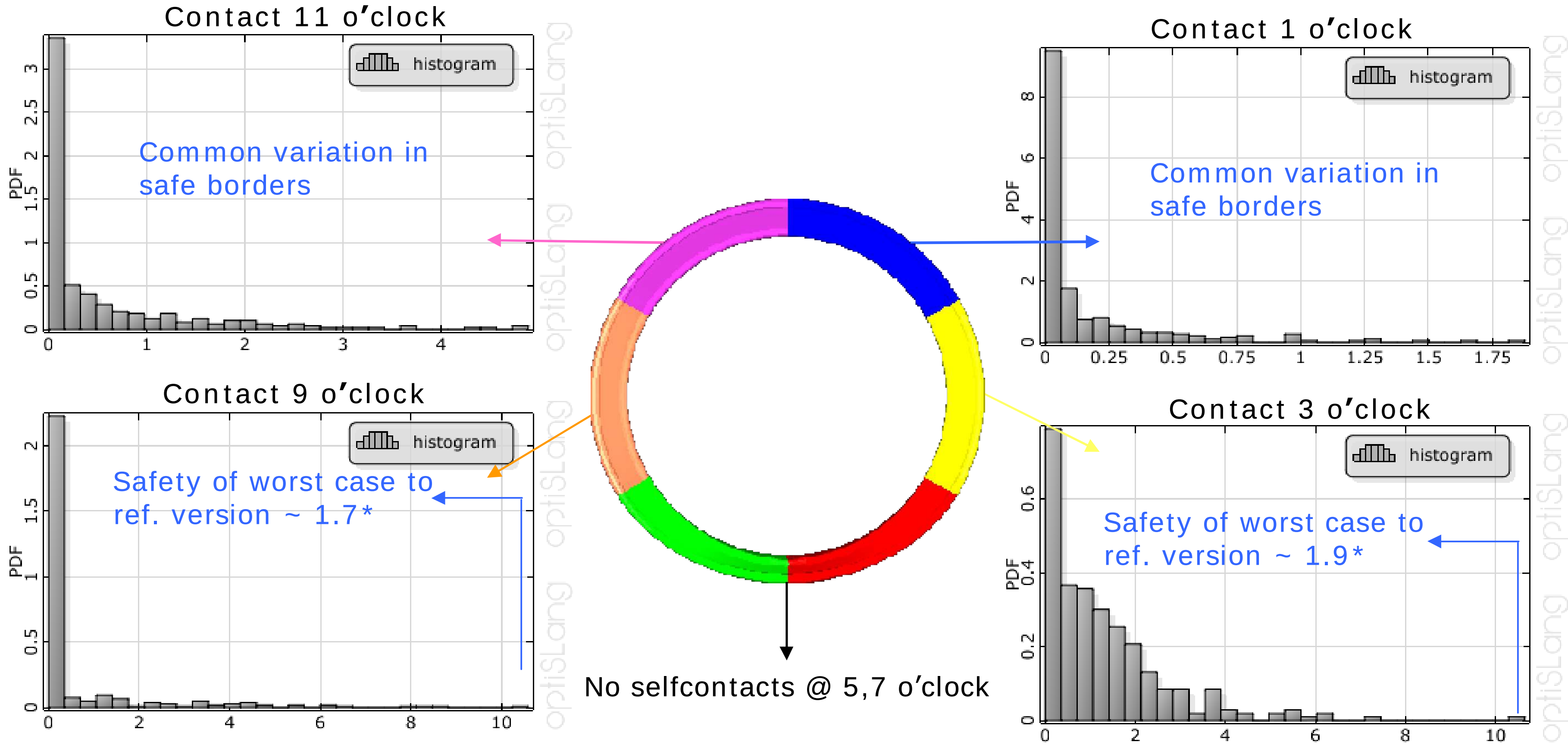
- Simulation model derived from approved "Optimized design for production" – real part
- Purpose of study is to get picture about common variance of bellow properties (contacts and transmitted forces) caused by production (Material variation was not considered)
- Statistical data of wall thicknesses from bellow products gathered and recalculated on "scale factor"
- Parameterization: same parameters as optimization – 40 parameters (scale factors)
- Load case — transformed movement from test bench
- Latin Hypercube sampling — 300 designs

Scale factor



Statistic data			
Min:	0.79	Max:	1.22
Mean:	1.005	Sigma:	0.07247
CV:	0.07213		
Skewness:	0.002729	Kurtosis:	2.944
Defined PDF: Normal			
Mean:	1.005	Sigma:	0.07241

Variation of contact forces



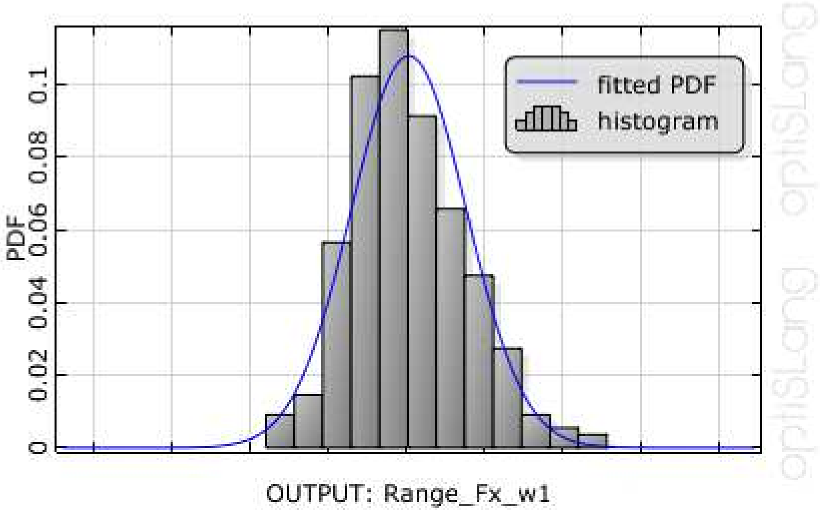
- Prediction shows low danger of wear out caused by selfcontacts. Limits for contact forces estimated from experience on studied parts.

* Comparison of worst case with nominal state of reference version (we did not perform stochastic study on reference version)

Variation of transmitted forces

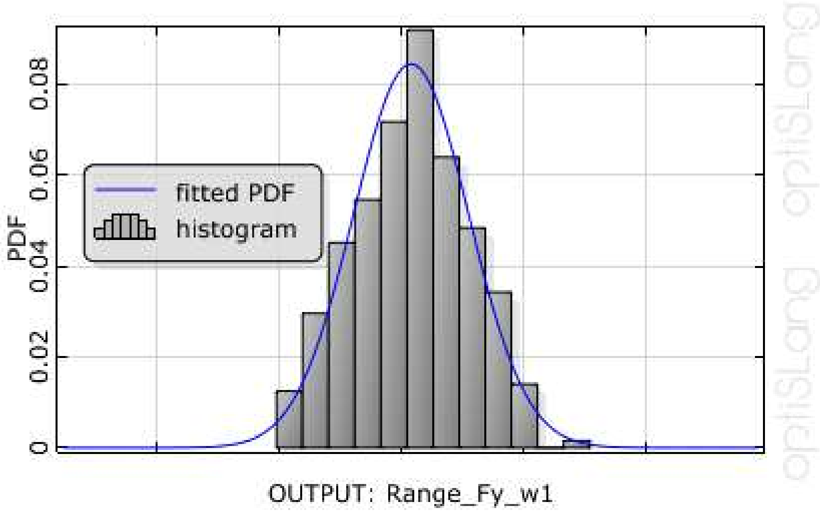
- Transmitted forces show certain variance that can have impact on noise and stability of washer
- Horizontal force can vary within ~15% from nominal force
- Vertical force can vary within ~35% from nominal force

Horizontal force



3σ = 15% of mean value

Vertical force



3σ = 35% of mean value

Conclusion

- Bellow is a strongly nonlinear system
- Its study is a complex problem about finding compromise between selfcontacts (wear out) and transmitted force (cabinet behavior)
- Automation and tools of OptiSlang significantly simplified study of bellow and made it transparent
  - Enabled to find dependencies between inputs and desired outputs within DOE and identify strong and important parameters and its tendencies
  - Using genetic optimization has been found new optimized design
  - Optimized design with few modifications verified by robustness study
- Bellow with optimized design has been approved for production