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Modal correlation of a brake caliper – boundary conditions optimization

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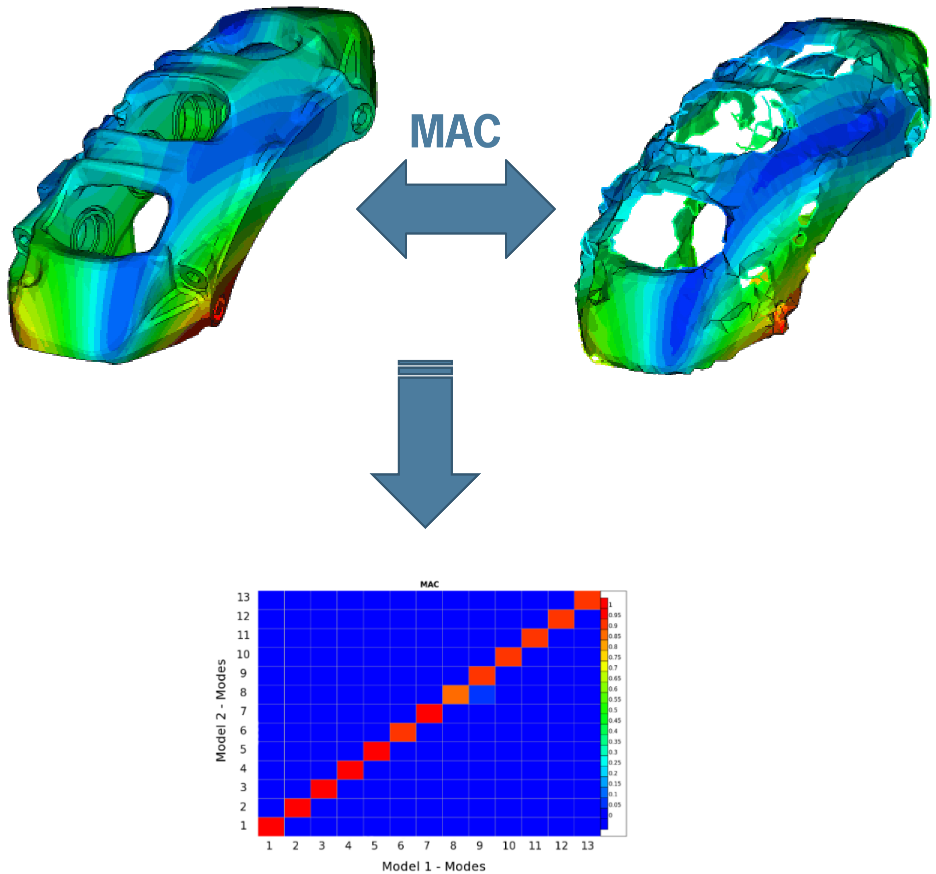


1.1 Introduction

> Modal correlation of brake components is essential part of complex NVH simulations.

> In order to have reliable simulation results modal properties of every component have to be examined carefully and compared with measured data.

> Modal assurance criterion (MAC) is being widely used to determine a measure of linear dependency between two eigenvectors.

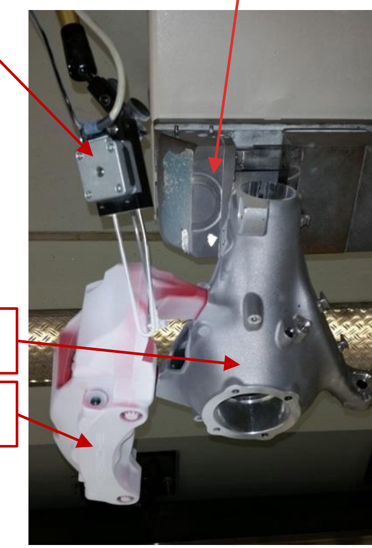
> Usually the standard correlation procedure consists of the following points:
> - Eigenvectors produced by FEM simulation are compared with experimentally determined eigenvectors using MAC.
> - In case MAC values show a poor correlation the simulation model has to be updated in order to describe the modal parameters properly.
> - Finally, the updated model is examined and subsequently an optimization of some of the model parameters can be done.

> We put effort into proper definition of the following properties:
> - Material properties, connections in the model, boundary conditions if necessary.

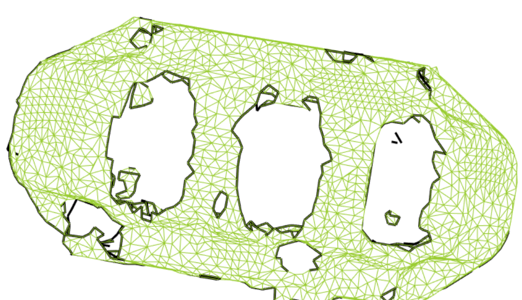
> **Only a properly correlated model can produce reliable results.**

2.1 Measurement and simulation setup

Measurement



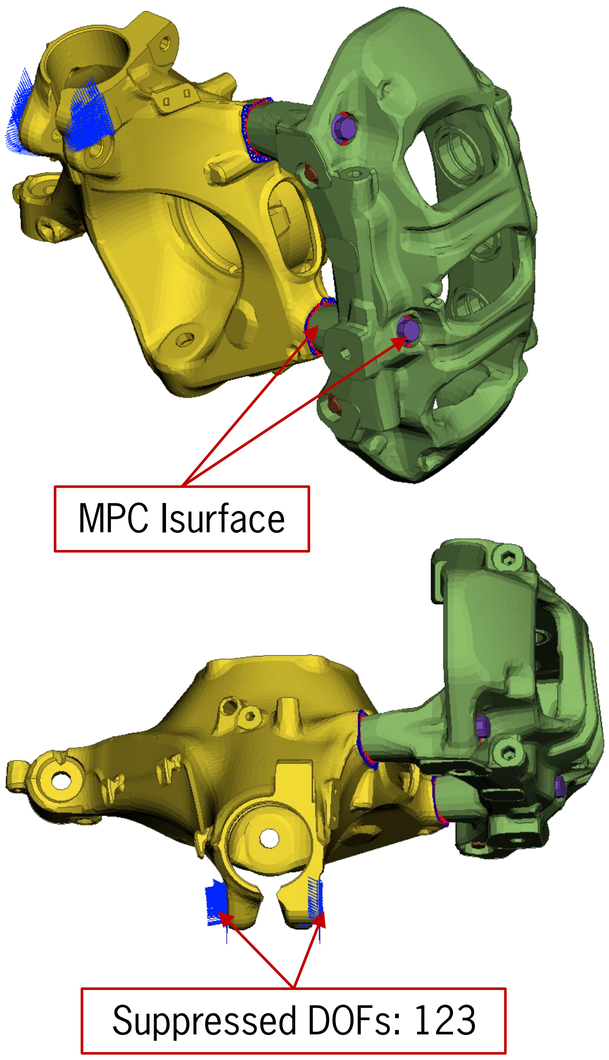
- The brake caliper is mounted on a steering knuckle, which is fully constrained in a clamping device.
- The steering knuckle is clamped near the suspension strut mounts.
- Experimental modal analysis (EMA) has been carried out using an automated impact hammer and 3D scanning laser vibrometer.
- Measurement setup:
  - 2450 measurement points on the caliper surface, exact match with FEA nodes => improved correlation accuracy
  - 16 eigenvectors have been extracted (up to 8 kHz)



2.2 Measurement and simulation setup

Simulation

- FEM simulation respects the measurement setup.
- The steering knuckle is suppressed in all DOFs (123) at clamped faces.
- The brake caliper is connected with the knuckle by MPC Isurface.
- Bolted connection uses MPC Isurface as well.
- Modal analysis up to 8.5 kHz:
  - 61 eigenvectors have been calculated
  - higher number of eigenvectors due to simulation of a complete assembly

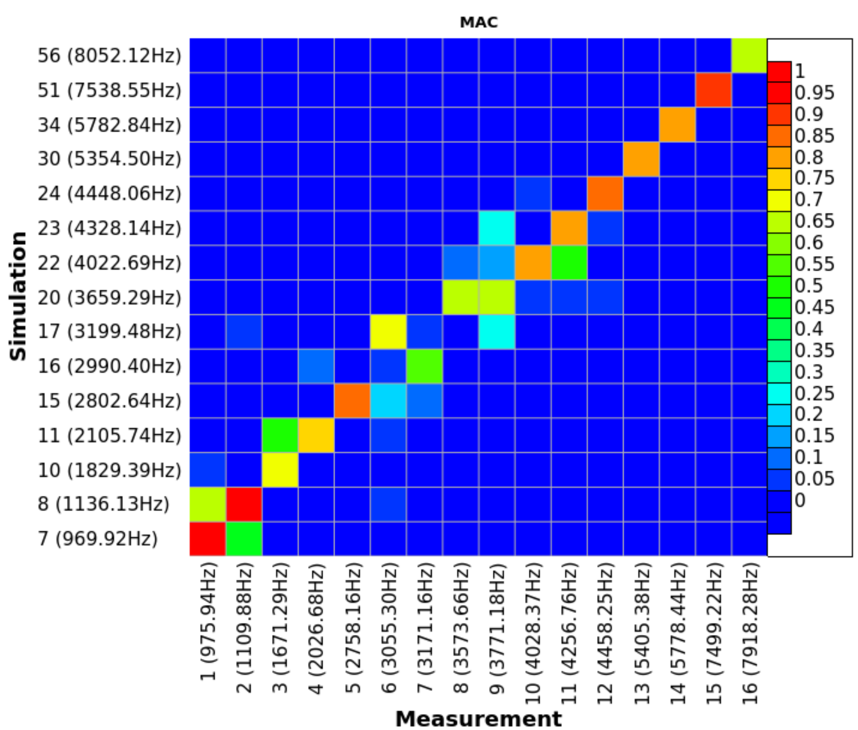


3.1 Modal correlation

Initial results

> MAC matrix is reduced only to the most correlated eigenmodes for every eigenmode from EMA.

> The modal correlation shows globally low MAC values and high frequency differences.



Brake caliper - initial model					
Measurement		Simulation		MAC	Δf
Mode1	f1 [Hz]	Mode2	f2 [Hz]	[-]	[%]
1	976	7	970	0.97	-0.6
2	1110	8	1136	0.95	2.3
3	1671	10	1829	0.73	8.6
4	2027	11	2106	0.76	3.8
5	2758	15	2803	0.88	1.6
6	3055	17	3199	0.73	4.5
7	3171	16	2990	0.55	-5.7
8	3574	20	3659	0.68	2.3
9	3771	20	3659	0.66	-3.0
10	4028	22	4023	0.82	-0.1
11	4257	23	4328	0.83	1.6
12	4458	24	4448	0.88	-0.2
13	5405	30	5355	0.80	-0.9
14	5778	34	5783	0.81	0.1
15	7499	51	7539	0.93	0.5
16	7918	56	8052	0.68	1.7

MAC	0		1
Δf	-10%		10%

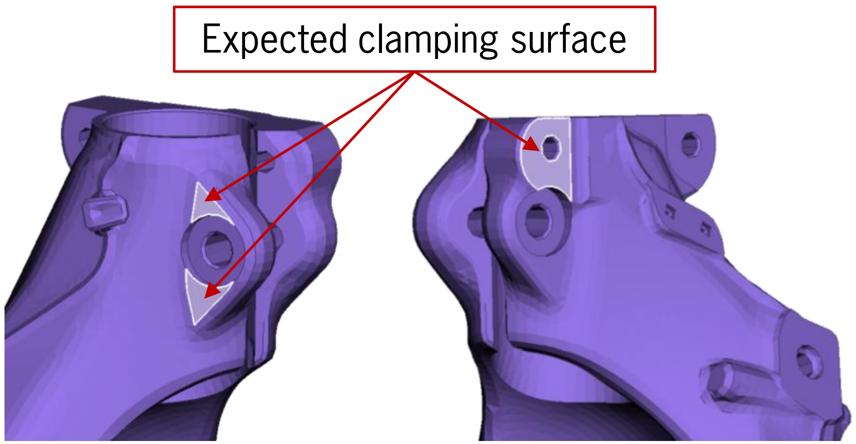
3.2 Modal correlation

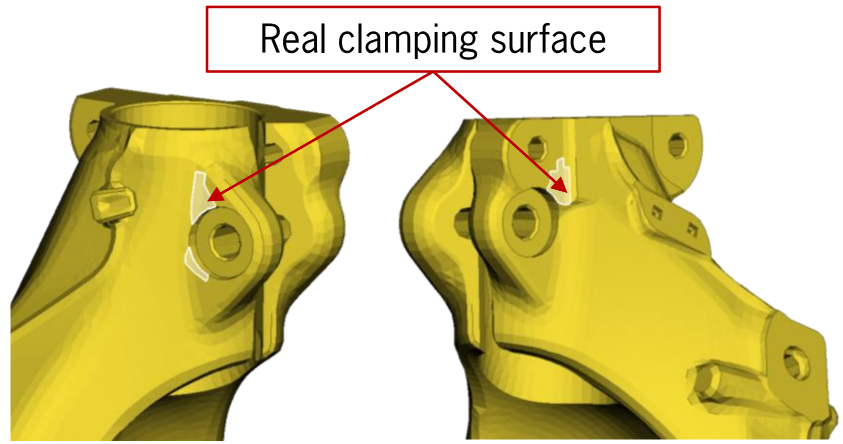
Updated model

> Due to unacceptable results the parts used for experimental modal analysis have been properly examined and the simulation model has been updated.

> Following properties have been updated:

- Material properties (only slight change, initial values were close to measured quantities)
- Boundary conditions - the real clamping surface differed the expected surface, where the boundary conditions were applied

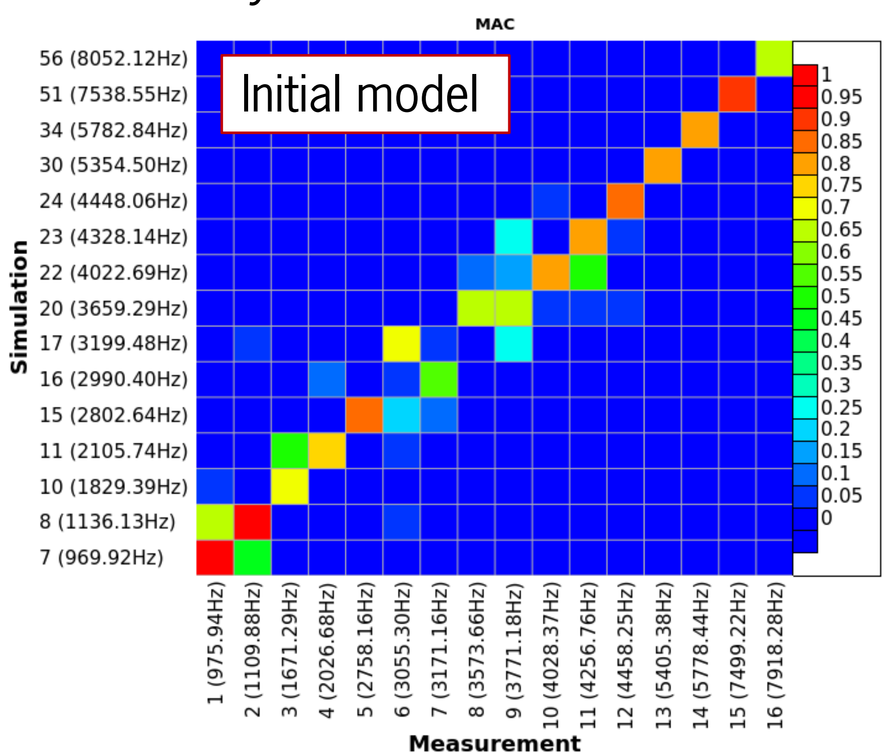


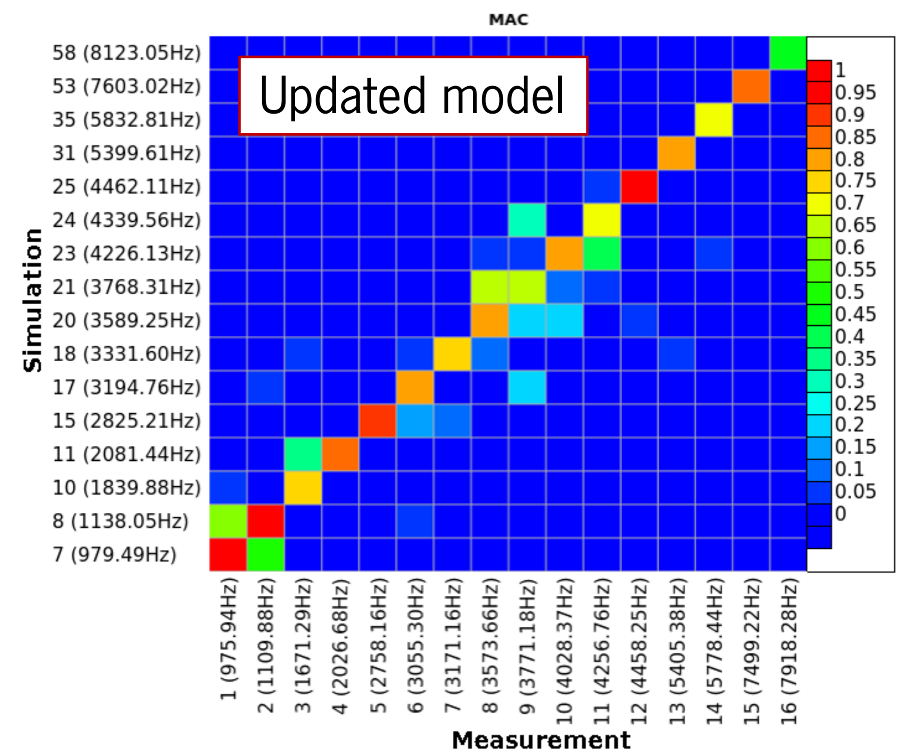


3.3 Modal correlation

Comparison

> Although the updated model shows improvement in MAC values, the global correlation is still not satisfactory:





3.4 Modal correlation

Comparison

> Frequency differences are still too high.

> Most of the simulation eigenmodes have higher frequencies => Mounting too stiff?

Brake caliper - initial model

Measurement		Simulation		MAC	Δf
Mode1	f1 [Hz]	Mode2	f2 [Hz]	[-]	[%]
1	976	7	970	0.97	-0.6
2	1110	8	1136	0.95	2.3
3	1671	10	1829	0.73	8.6
4	2027	11	2106	0.76	3.8
5	2758	15	2803	0.88	1.6
6	3055	17	3199	0.73	4.5
7	3171	16	2990	0.55	-5.7
8	3574	20	3659	0.68	2.3
9	3771	20	3659	0.66	-3.0
10	4028	22	4023	0.82	-0.1
11	4257	23	4328	0.83	1.6
12	4458	24	4448	0.88	-0.2
13	5405	30	5355	0.80	-0.9
14	5778	34	5783	0.81	0.1
15	7499	51	7539	0.93	0.5
16	7918	56	8052	0.68	1.7

Brake caliper - updated model

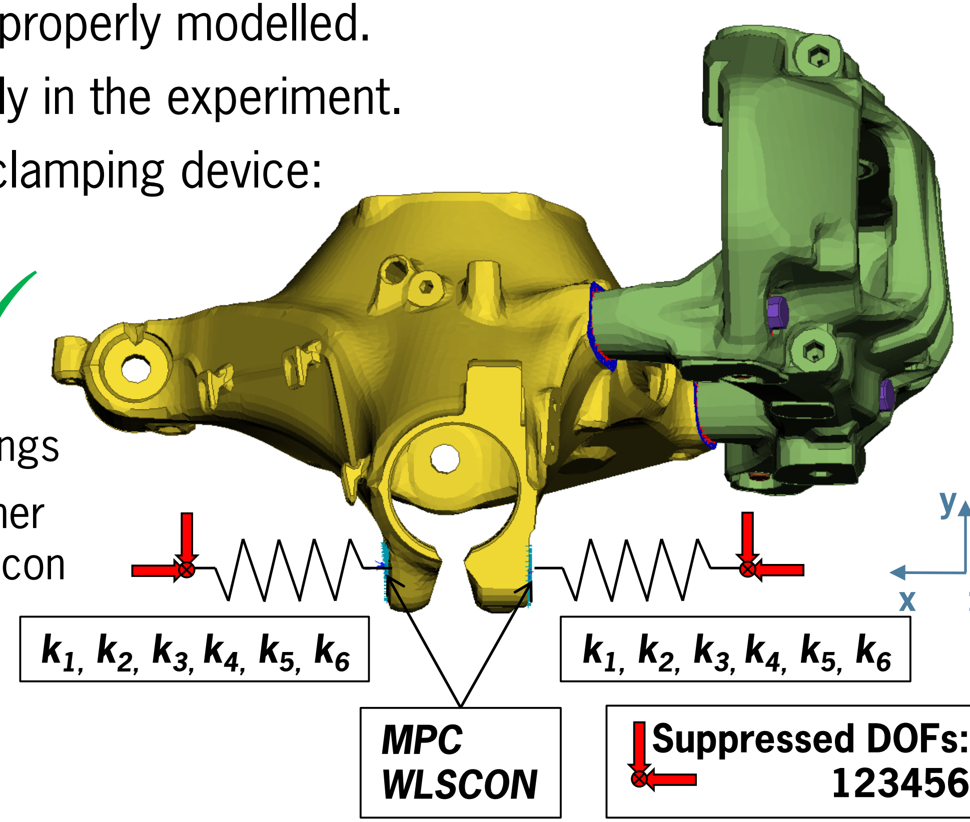
Measurement		Simulation		MAC	Δf
Mode1	f1 [Hz]	Mode2	f2 [Hz]	[-]	[%]
1	976	7	979	0.98	0.4
2	1110	8	1138	0.98	2.5
3	1671	10	1840	0.76	9.2
4	2027	11	2081	0.90	2.6
5	2758	15	2825	0.90	2.4
6	3055	17	3195	0.85	4.4
7	3171	18	3332	0.75	4.8
8	3574	20	3589	0.83	0.4
9	3771	21	3768	0.67	-0.1
10	4028	23	4226	0.84	4.7
11	4257	24	4340	0.72	1.9
12	4458	25	4462	0.98	0.1
13	5405	31	5400	0.85	-0.1
14	5778	35	5833	0.75	0.9
15	7499	53	7603	0.89	1.4
16	7918	58	8123	0.49	2.5

MAC	0	1
Δf	-10%	10%

4.1 Optimization of boundary conditions

Optimization setup

- Mounting of the steering knuckle seems to be improperly modelled.
- Absolutely rigid mounting cannot be created easily in the experiment.
- Necessary to determine correct stiffness of the clamping device:
  - Modelling of the complete clamping device ✗
  - Optimization of the spring stiffness coefficients ✓
- Model description:
  - Rigid constraints were replaced by compliant springs
  - SPRING6 element, one end is suppressed, the other one is connected to the knuckle through MPC Wlscon
  - Both springs have the same stiffness coefficients



4.2 Optimization of boundary conditions

Optimization setup

- **Design variables:** $k_1, k_2, k_3, k_4, k_5, k_6$
- **Design constraints:** 7 eigenfrequencies (picked eigenfreq. of sufficiently correlated modes)
- **Objective function:** Sum of the quadratic relative differences between simulated eigenfrequencies and measured eigenfrequencies (design constraints)
  - Used library function, type 13

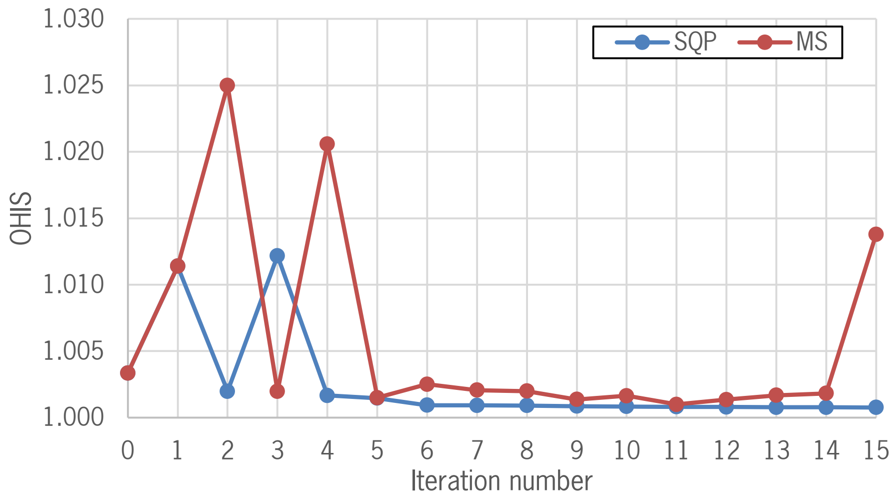
$$\mathrm{f}(x_i; i = 1, n) = c_0 + \sum_{i=1}^{n} c_i x_i^2$$

- **Design objective:** Finding a minimum of the objective function => to minimize frequency differences
- **Optimization methods:** Sequential Quadratic Programming (SQP) and MultiStart (MS) method
- **Initial values of the design variables:**
  - $k_1 = k_2 = k_3 = 5.0E+5$ N/mm
  - $k_4 = k_5 = k_6 = 5.0E+8$ Nmm/rad

4.3 Optimization of boundary conditions

Optimization results

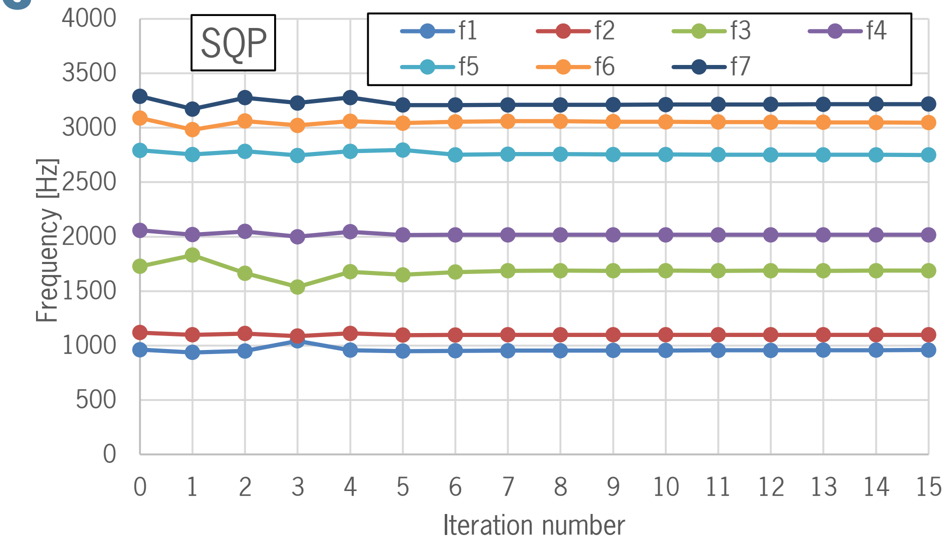
> Tested two optimization algorithms – SQP and MS

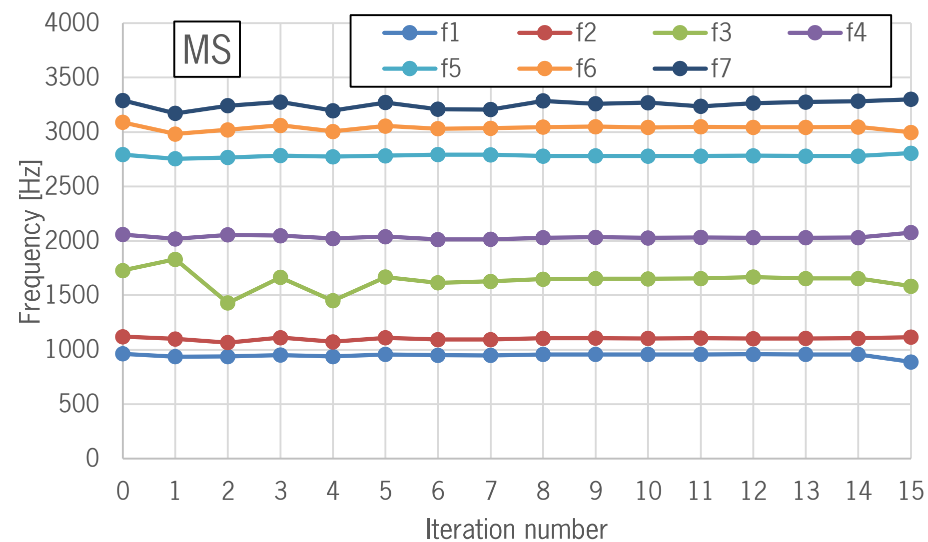


> SQP calculation time ca. 13 min (15 iterations), 4 CPUs @ 3.3 GHz

> Multi Start method terminated after 100 iterations

> Optimum iterations: 13 (SQP) and 11 (MS)



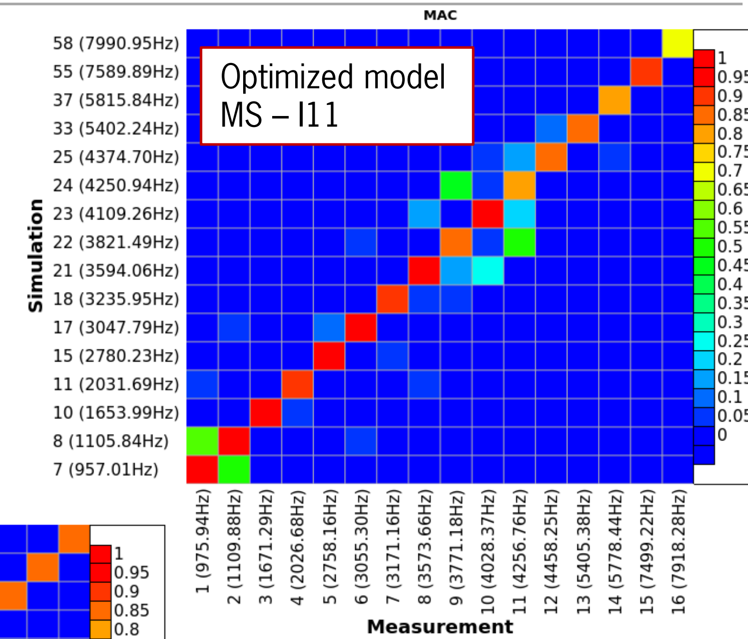


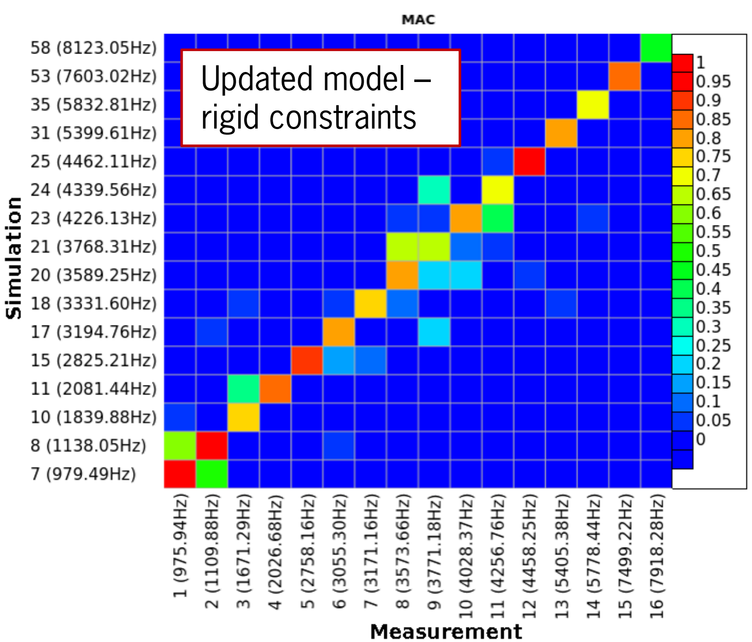
4.4 Optimization of boundary conditions

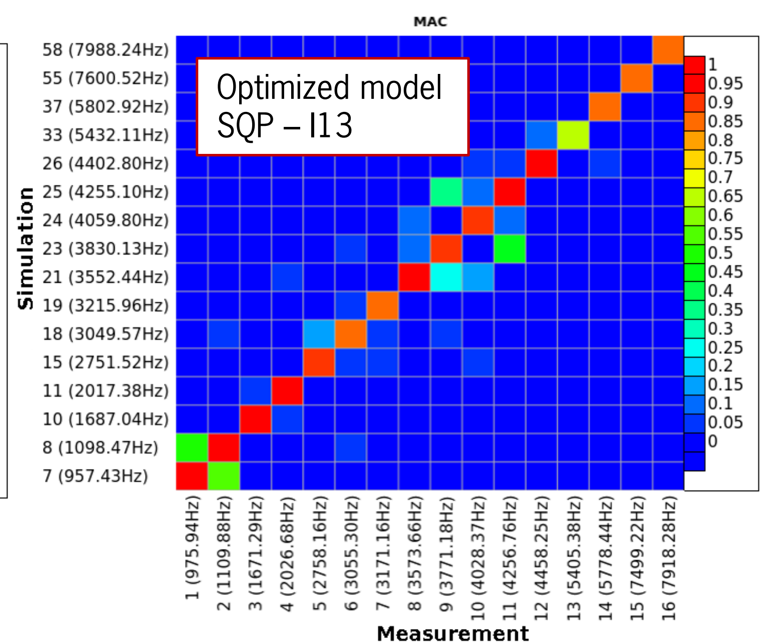
Optimized model results

> Great improvement of the correlation through the complete frequency range.

> MAC matrix almost diagonal.







4.5 Optimization of boundary conditions

Optimized model results

MAC	0	1
Δf	-10%	10%

> Frequency differences below 2% through the complete frequency range

Brake caliper - updated model (rigid cons.)

Measurement		Simulation		MAC	Δf
Mode1	f1 [Hz]	Mode2	f2 [Hz]	[-]	[%]
1	976	7	979	0.98	0.4
2	1110	8	1138	0.98	2.5
3	1671	10	1840	0.76	9.2
4	2027	11	2081	0.90	2.6
5	2758	15	2825	0.90	2.4
6	3055	17	3195	0.85	4.4
7	3171	18	3332	0.75	4.8
8	3574	20	3589	0.83	0.4
9	3771	21	3768	0.67	-0.1
10	4028	23	4226	0.84	4.7
11	4257	24	4340	0.72	1.9
12	4458	25	4462	0.98	0.1
13	5405	31	5400	0.85	-0.1
14	5778	35	5833	0.75	0.9
15	7499	53	7603	0.89	1.4
16	7918	58	8123	0.49	2.5

Average MAC 0.82

Brake caliper - optimized model (SQP I13)

Measurement		Simulation		MAC	Δf
Mode1	f1 [Hz]	Mode2	f2 [Hz]	[-]	[%]
1	976	7	957	0.99	-1.9
2	1110	8	1098	0.99	-1.0
3	1671	10	1687	0.97	0.9
4	2027	11	2017	0.96	-0.5
5	2758	15	2752	0.94	-0.2
6	3055	18	3050	0.89	-0.2
7	3171	19	3216	0.87	1.4
8	3574	21	3552	0.96	-0.6
9	3771	23	3830	0.93	1.5
10	4028	24	4060	0.92	0.8
11	4257	25	4255	0.95	0.0
12	4458	26	4403	0.95	-1.2
13	5405	33	5432	0.70	0.5
14	5778	37	5803	0.87	0.4
15	7499	55	7601	0.90	1.3
16	7918	58	7988	0.88	0.9

Average MAC 0.92

Brake caliper - optimized model (MS I11)

Measurement		Simulation		MAC	Δf
Mode1	f1 [Hz]	Mode2	f2 [Hz]	[-]	[%]
1	976	7	957	0.98	-1.9
2	1110	8	1106	0.99	-0.4
3	1671	10	1654	0.98	-1.0
4	2027	11	2032	0.91	0.2
5	2758	15	2780	0.98	0.8
6	3055	17	3048	0.97	-0.2
7	3171	18	3236	0.93	2.0
8	3574	21	3594	0.95	0.6
9	3771	22	3821	0.87	1.3
10	4028	23	4109	0.97	2.0
11	4257	24	4251	0.84	-0.1
12	4458	25	4375	0.90	-1.9
13	5405	33	5402	0.88	-0.1
14	5778	37	5816	0.84	0.6
15	7499	55	7590	0.92	1.2
16	7918	58	7991	0.72	0.9

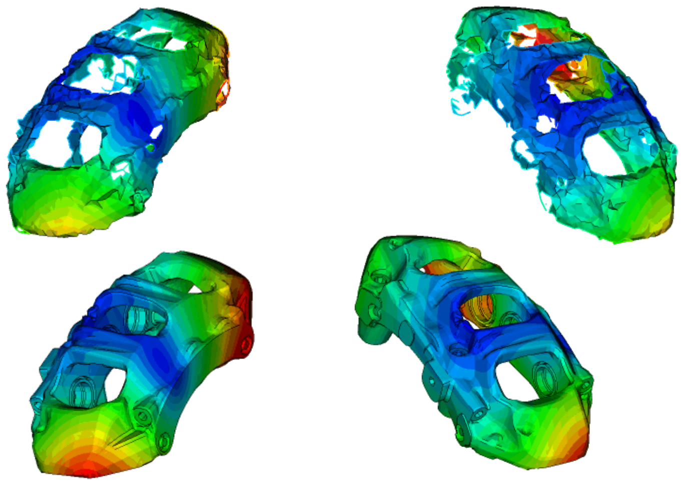
Average MAC 0.91

5.1 Modal shapes - selected

Measurement	
Freq.	976 Hz
Mode	1

MAC	0.99

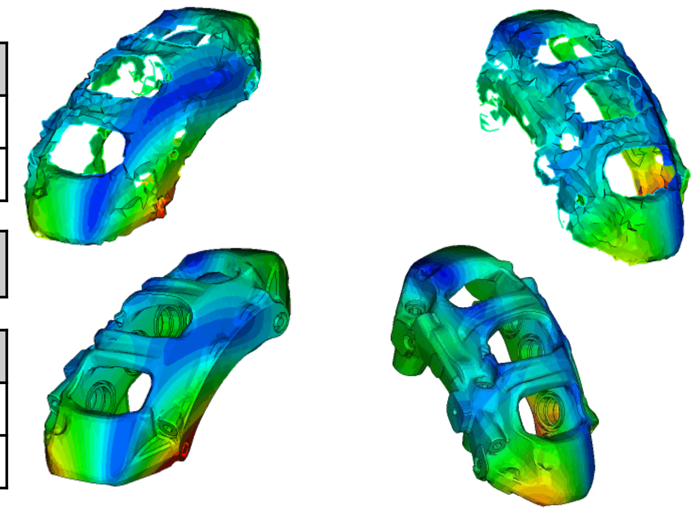
Simulation (SQP)	
Freq.	957 Hz
Mode	7



Measurement	
Freq.	1671 Hz
Mode	3

MAC	0.97

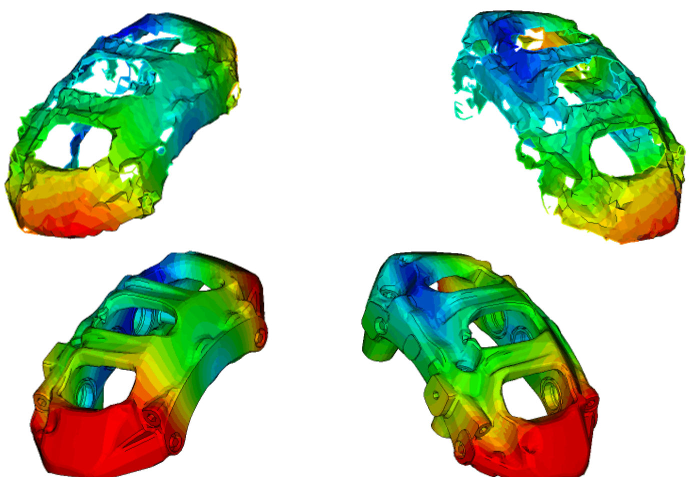
Simulation (SQP)	
Freq.	1687 Hz
Mode	10



Measurement	
Freq.	1110 Hz
Mode	2

MAC	0.99

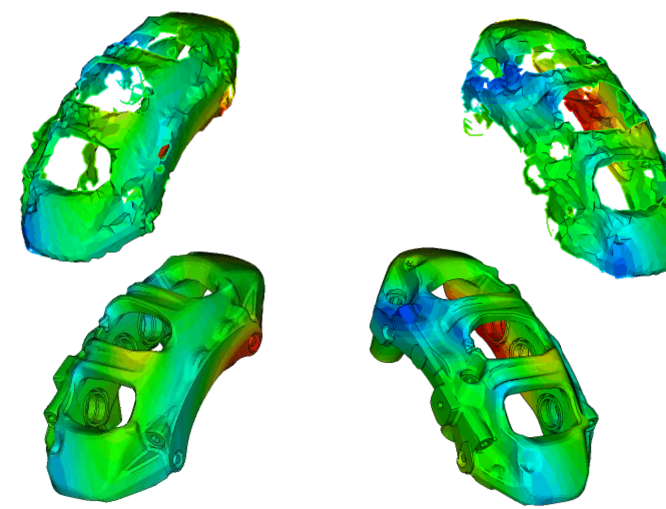
Simulation (SQP)	
Freq.	1098 Hz
Mode	8



Measurement	
Freq.	2027 Hz
Mode	4

MAC	0.96

Simulation (SQP)	
Freq.	2017 Hz
Mode	11

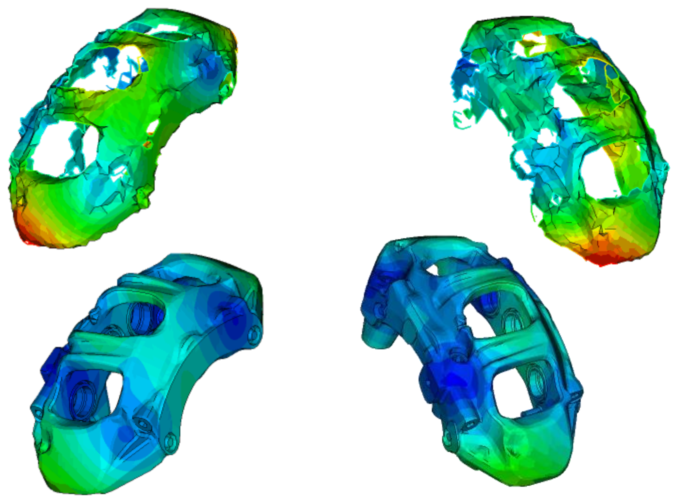


5.2 Modal shapes - selected

Measurement	
Freq.	2758 Hz
Mode	5

MAC	0.94

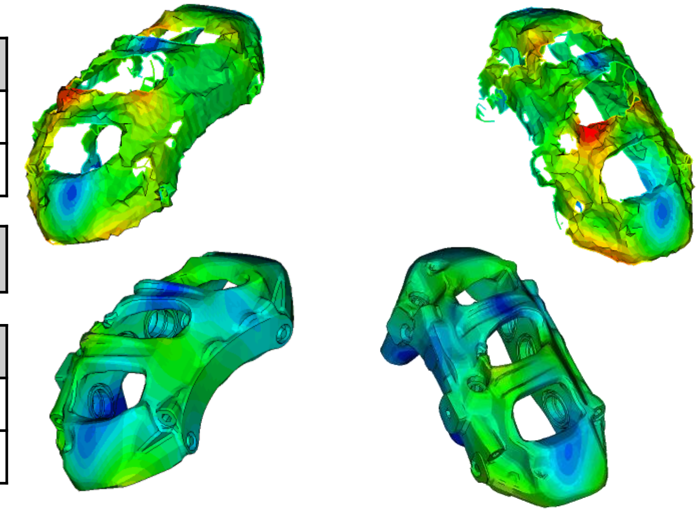
Simulation (SQP)	
Freq.	2752 Hz
Mode	15



Measurement	
Freq.	3171 Hz
Mode	7

MAC	0.87

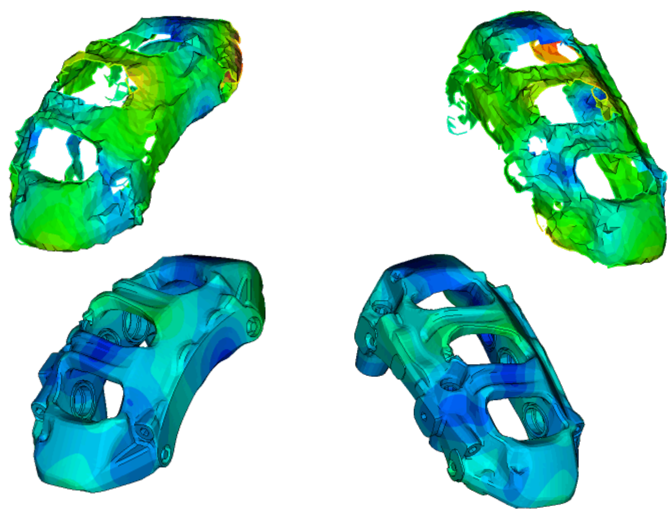
Simulation (SQP)	
Freq.	3216 Hz
Mode	19



Measurement	
Freq.	3055 Hz
Mode	6

MAC	0.89

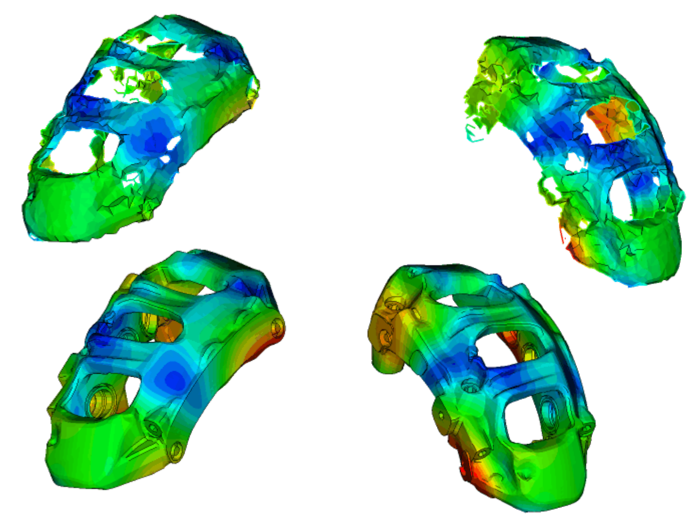
Simulation (SQP)	
Freq.	3050 Hz
Mode	18



Measurement	
Freq.	3574 Hz
Mode	8

MAC	0.96

Simulation (SQP)	
Freq.	3552 Hz
Mode	21



6.1 Summary

- Experimental model has to be properly examined for a correct correlation.
- Discrepancy in the initial correlation results caused mainly by the boundary conditions definition.
- Both optimization methods (SQP and MS) applicable.
- Updated FEA model with correct material properties and optimized boundary conditions shows decent correlation results through the complete frequency range:

	Rigid cons.	Optimized cons.
Min. MAC	0.49	0.70
Max. MAX	0.98	0.99
Average MAC	**0.82**	**0.92**
Max. freq. difference	9.2 %	1.9 %

- Further development:
  - Different mounting of the steering knuckle in order to define FEA boundary conditions more easily