Bearing stiffness

Evaluating bearing stiffness using SKF SimPro

Contents

1. Background & scope

Application engineers and design engineers are frequently interested in calculating the bearing stiffness. However, there is often a different understanding of what bearing stiffness really means and what to do with the resulting bearing stiffness values.

The bearing stiffness can be evaluated in different ways and the results and their purpose can be different as well. This document will show the different methods to evaluate the bearing stiffness, their meaning and differences, as well as their limitations. Most of these methods can be applied using one of SKF’s SimPro tools such as SKF SimPro Quick, SKF SimPro Expert or SKF SimPro Spindle.

Some typical examples are given for what purpose the particular result is used. Please note that the used operating conditions and bearings are not related to a real application case. The examples show in a general way how to create a model and how the results can be interpreted.

2. Bearing stiffness methods

The stiffness of a rolling bearing is characterized by the magnitude of the elastic deformation in the bearing under load and depends not only on bearing type, but also on bearing size, bearing internal geometry and operating conditions. When selecting a bearing type based on stiffness requirements, you should consider that, for bearings with the same size:

- stiffness is higher for roller than for ball bearings
- stiffness is higher for full complement bearings than for the corresponding bearing with a cage
- stiffness is higher for hybrid bearings than for the corresponding all-steel bearing
- stiffness can be enhanced by applying a preload

The stiffness of a body is a measure of its resistance to deformation changes. The stiffness behavior can be different for different components. For example, a normal spring element has a linear stiffness behavior. This means that the slope of the spring curve is constant.

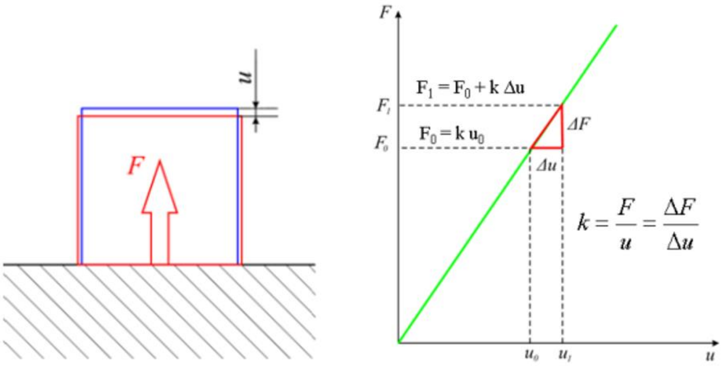


Fig. 1: linear behaviour

For a rolling bearing the stiffness behavior is non-linear (the contact area is changing with the load due to the bearing inner geometry). This means that the slope of the spring curve is NOT constant and is always changing with the variation of the applied loading.

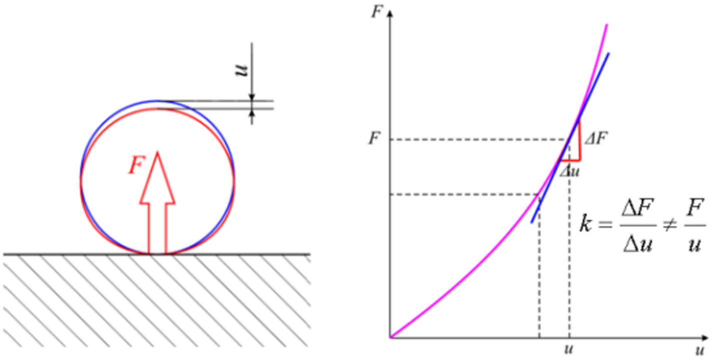


Fig. 2: non-linear behaviour

Some more details about the following bearing stiffness evaluation methods will be described:

- Bearing spring curve
- Bearing contact spring curve
- Bearing stiffness matrix

It should be understood that the following must considered in all cases described in this document:

- When looking at bearing stiffness, we consider the contact stiffness in the rolling contacts only. The bearing inner and outer ring are considered rigid, i.e. infinitely stiff. Neither does the bearing stiffness include the elasticity of surrounding components such as a housing.

2.1 Bearing spring curve

The spring curve of the bearing represents the behaviour of the bearing in one degree of freedom (DOF). It is the relation between the bearing load and the bearing displacement, or the bearing moment and corresponding misalignment. This characteristic is valid for a specific bearing with a defined load range and for one specific DOF (pure radial, pure axial direction, pure moment). The spring curve is calculated with zero bearing internal clearance.

The spring curve of the bearing shows the force-displacement relation (or moment-misalignment relation) in one DOF (NO combined loading conditions). The stiffness value of the bearing is then the slope at a certain force (or moment).

As shown in fig. 2, the behaviour of a rolling bearing is non-linear. The stiffness is changing with the load. To calculate the stiffness for one loading condition it is therefore NOT correct to use the total force F and the total displacement u. Instead, one has to use a (small) variation of F (ΔF) and u (Δu) at a specific point in the curve:

- Radial or axial stiffness = $\Delta F/\Delta u$
- Moment stiffness = $\Delta M/\Delta \phi$

The bearing spring curve is valid under the following conditions:

- pure radial force/radial displacement --> NO moments, NO misalignments
- pure axial force/axial displacement --> NO moments, NO misalignments
- pure moment/misalignment --> NO radial/axial forces, NO displacements

It should be noted that in reality, the above conditions almost never hold in a shaft-bearing-housing system. Therefore the bearing spring curve is only a rough approach to predict the behaviour of the bearing in a shaft-bearing-housing system.

The bearing spring curve can be used:

- to evaluate the axial preload for a given axial pre-displacement
- for the evaluation of critical speeds of a shaft

2.2 Bearing contact spring curve

The spring curve of the contact represents the behaviour of the rolling contact (inner ring-rolling element-outer ring or IR-RE-OR). It is the relation between the normal contact force on the rolling element and the corresponding total (elastic) contact deformation (IR-RE and RE-OR).

This approach does not represent the bearing behaviour and the stiffness of the bearing as such, but the behaviour of the rolling elements within the bearing.
The rolling elements can be replaced by spring elements where this (nonlinear) spring characteristic can be given as property (usually a single spring for ball bearings and at least two springs for a roller bearing, fig. 3).

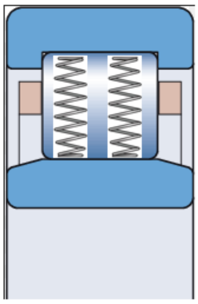


Fig. 3: Bearing contact springs

When using this approach, in FE (Finite Element) tools for example, the rolling elements can be modelled by springs. With this also in the FE tools the influence of the surrounding parts (deformations of housings, bearing rings, etc.) on the bearing loaded zone can be evaluated.

The contact spring curve is often used in FE tools, where the rolling elements are represented by springs.

2.3 Bearing stiffness matrix

The bearing stiffness matrix represents the stiffness of a bearing in all degrees of freedom, but only for ONE specific loading condition. The stiffness is valid when the fluctuations (Δu) are small compared to the total deflections (u) of the bearing rings.

The stiffness matrix for the bearing is calculated based on the behavior of the complete shaft-bearing-housing system in SKF SimPro. This includes the operating clearance/preload, shaft bending, misalignments, reaction forces and moments, etc. for the complete system.
When something changes in the shaft-system (e.g. clearance of one bearing), the behavior of the system and therewith the stiffness of any bearing in the system changes.

- ➔ Each parameter can influence each other in a shaft-bearing-housing system!

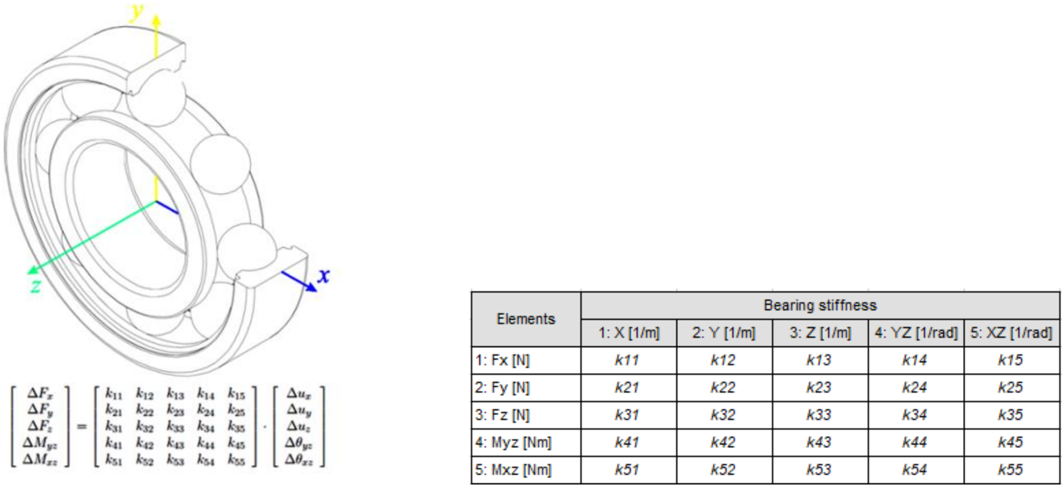
Therefore the calculation of the bearing stiffness matrix for a model with single bearing loads needs to be handled with care, as it does not represent the behavior of the bearing when subjected to loads applied to the system.

It is also important to note that in any bearing where the rolling element can have a non-zero contact angle (this is valid for most rolling bearings except cylindrical and needle roller bearings) there is a relationship between radial and axial load and displacement. E.g. a spherical roller bearing subjected to a combined load, if given a small change in axial load, affects the displacement both in axial and radial direction.

This means that the bearing stiffness (fig. 4) cannot be evaluated in translational directions based on the bearing stiffness matrix diagonal elements ($k11$, $k22$, $k33$) only. The stiffness elements in other directions have to be considered in order to get an accurate result. Similarly it is not possible to evaluate misalignment stiffness by simply looking at e.g. the $k23$ or $k13$ elements.

The bearing stiffness matrix is often used:

- in FE tools to simulate the behaviour of a bearing in all DOFs
- in multi body simulations (MBS)



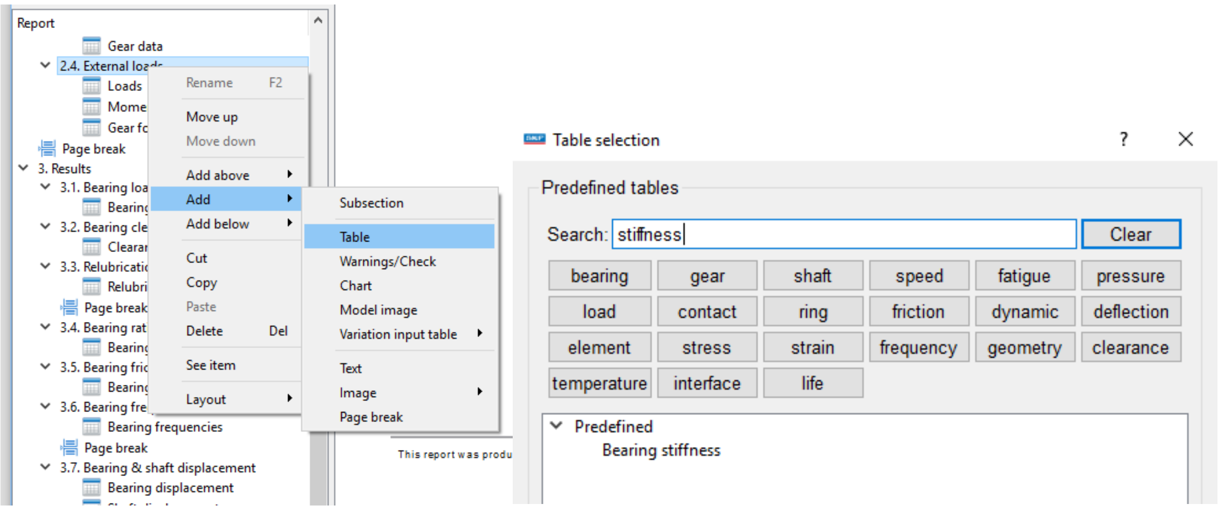
$$\begin{bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \\ \Delta M_{yz} \\ \Delta M_{xz} \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} \\ k_{31} & k_{32} & k_{33} & k_{34} & k_{35} \\ k_{41} & k_{42} & k_{43} & k_{44} & k_{45} \\ k_{51} & k_{52} & k_{53} & k_{54} & k_{55} \end{bmatrix} \cdot \begin{bmatrix} \Delta u_x \\ \Delta u_y \\ \Delta u_z \\ \Delta \theta_{yz} \\ \Delta \theta_{xz} \end{bmatrix}$$

Elements	Bearing stiffness				
	1: X [1/m]	2: Y [1/m]	3: Z [1/m]	4: YZ [1/rad]	5: XZ [1/rad]
1: Fx [N]	*k11*	*k12*	*k13*	*k14*	*k15*
2: Fy [N]	*k21*	*k22*	*k23*	*k24*	*k25*
3: Fz [N]	*k31*	*k32*	*k33*	*k34*	*k35*
4: Myz [Nm]	*k41*	*k42*	*k43*	*k44*	*k45*
5: Mxz [Nm]	*k51*	*k52*	*k53*	*k54*	*k55*

Fig. 4: Bearing stiffness matrix

2.3.1 How to extract the bearing stiffness matrix?

In SKF SimPro, the bearing stiffness matrix is added to the report by right-clicking in the report tree and choosing ‘Add’ --> ‘Table’. From the list of pre-defined tables, choose ‘Bearing stiffness’ from the list (or search for ‘stiffness’) and press the 'OK' button to add the table to the report.



Search: stiffness

Predefined
Bearing stiffness

Fig. 5: Bearing stiffness matrix extraction in SimPro

3. Examples

In the following examples a cylindrical roller bearing (CRB NU 210 ECP) and a deep groove ball bearing (DGBB 6210) are used to explain the different methods and how the stiffness can be evaluated. All calculations are done with rigid (i.e. infinitely stiff) rings. The rolling contact is elastic.

3.1 Bearing spring curve

A model with a single bearing is created in SKF SimPro Expert. To create a radial spring curve, a radial force in X-direction is applied. A radial force in Y-direction may lead to different results, as the position of the rolling elements can be different, depending on the number of rolling elements (rolling element 1 is always positioned on the X axis).
The bearing inner ring is grounded in axial direction to avoid axial movement. Also the rotational DOFs are constrained to avoid misalignment. This ensures a pure radial displacement.
The clearance and speed are set to zero (no centrifugal effect).

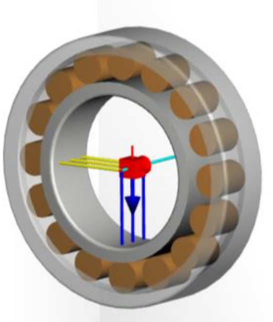


Fig. 6: single bearing model (CRB example)

The force is varied from 0 to 15000 N with a variation study. The force and the corresponding bearing displacement in X direction are plotted in a diagram (fig. 7).

As shown in this diagram the curves for the two bearings are not linear, i.e. the slope (stiffness) is different for each load. The higher the load, the stiffer the bearing. It is also seen that the stiffness of the roller bearing is higher than for the ball bearing.

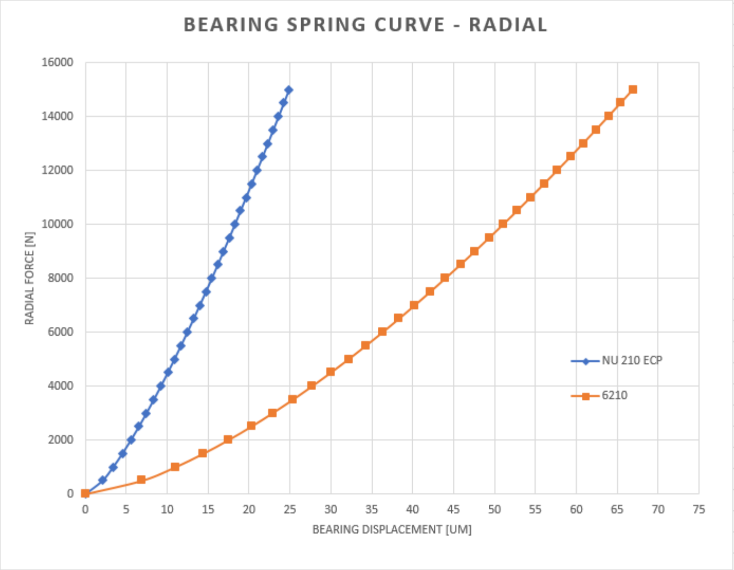


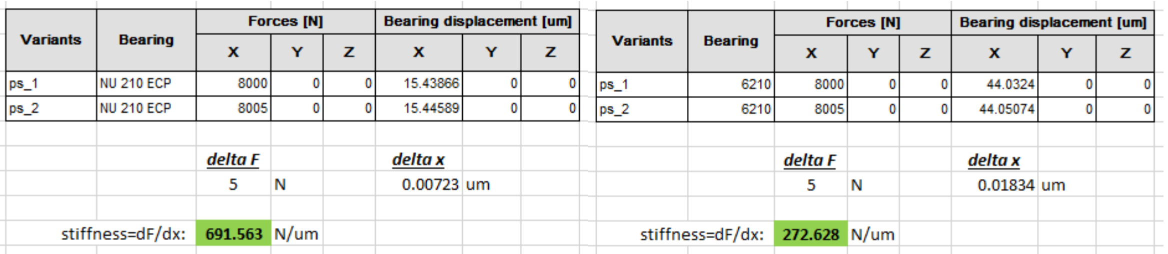
Fig. 7: Spring curve for the CRB and DGBB

The radial stiffness of the two bearings can be calculated from the spring curve. Here, the stiffness is evaluated for a load level of 8000 N. As described in chapter 2.1, NOT the total force (8000 N) and the corresponding total displacement can be used. In order to show the difference, here the wrong calculation is done.

CRB: 8000 N / 15.43866 um = 518.180 N/um
DGBB: 8000 N / 44.0324 um = 181.684 N/um

➔ WRONG stiffness values !

Instead, a small delta value has to be used at the load level where the stiffness should be calculated. A calculation in SKF SimPro is done for 8000 N and for 8005 N, i.e. ΔF is 5 N. The corresponding displacements are calculated and the Δu is used to calculate the stiffness value as $\Delta F / \Delta u$.

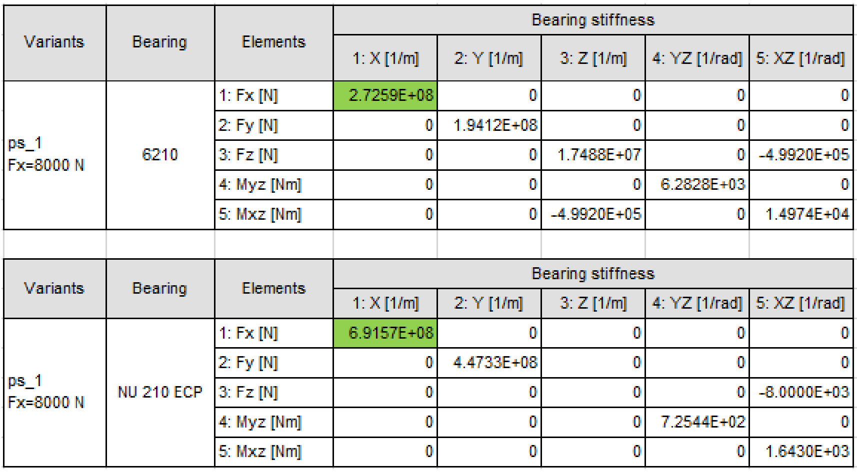


Variants	Bearing	Forces [N]			Bearing displacement [um]		
		X	Y	Z	X	Y	Z
ps_1	NU 210 ECP	8000	0	0	15.43866	0	0
ps_2	NU 210 ECP	8005	0	0	15.44589	0	0
		delta F			***delta x***		
		5	N		0.00723	um	
	stiffness=dF/dx:	**691.563**	N/um				

Variants	Bearing	Forces [N]			Bearing displacement [um]		
		X	Y	Z	X	Y	Z
ps_1	6210	8000	0	0	44.0324	0	0
ps_2	6210	8005	0	0	44.05074	0	0
		delta F			***delta x***		
		5	N		0.01834	um	
	stiffness=dF/dx:	**272.628**	N/um				

Fig. 8: calculated radial stiffness for the CRB and DGBB at 8000 N

The resulting radial stiffness values can be compared with the result of the bearing stiffness matrix (element k_{11} in fig. 9), when calculated under the **<u>same conditions</u>** (i.e. pure radial force and radial displacement, no misalignments, zero clearance, zero speed).



Variants	Bearing	Elements	Bearing stiffness				
			1: X [1/m]	2: Y [1/m]	3: Z [1/m]	4: YZ [1/rad]	5: XZ [1/rad]
ps_1 Fx=8000 N	6210	1: Fx [N]	2.7259E+08	0	0	0	0
		2: Fy [N]	0	1.9412E+08	0	0	0
		3: Fz [N]	0	0	1.7488E+07	0	-4.9920E+05
		4: Myz [Nm]	0	0	0	6.2828E+03	0
		5: Mxz [Nm]	0	0	-4.9920E+05	0	1.4974E+04

Variants	Bearing	Elements	Bearing stiffness				
			1: X [1/m]	2: Y [1/m]	3: Z [1/m]	4: YZ [1/rad]	5: XZ [1/rad]
ps_1 Fx=8000 N	NU 210 ECP	1: Fx [N]	6.9157E+08	0	0	0	0
		2: Fy [N]	0	4.4733E+08	0	0	0
		3: Fz [N]	0	0	0	0	-8.0000E+03
		4: Myz [Nm]	0	0	0	7.2544E+02	0
		5: Mxz [Nm]	0	0	0	0	1.6430E+03

Fig. 9: bearing stiffness matrix for the single bearings at 8000 N (same boundary conditions as for the spring curve !)

3.2 Bearing contact spring curve

A model with a single bearing is created in SKF SimPro Expert, similar as for the bearing spring curve.

With a single radial force, a loaded zone in the bearing with several loaded rolling elements is calculated. Depending on the applied load, the number of loaded rolling elements may vary.
A parameter study is performed where the radial load is varied:

- Loads for the CRB: 1000 N, 8000 N, 16000 N
- Loads for the DGBB: 1000 N, 5000 N, 10000 N

The sum of the inner ring and outer ring contact deformation is calculated.

In fig. 10 the rolling element load (Q) and the corresponding total contact deformation (u) are plotted. This represents the spring curve of the rolling contact of the bearing. The contact stiffness can be calculated as follows:

- Contact stiffness = $\Delta Q / \Delta u$

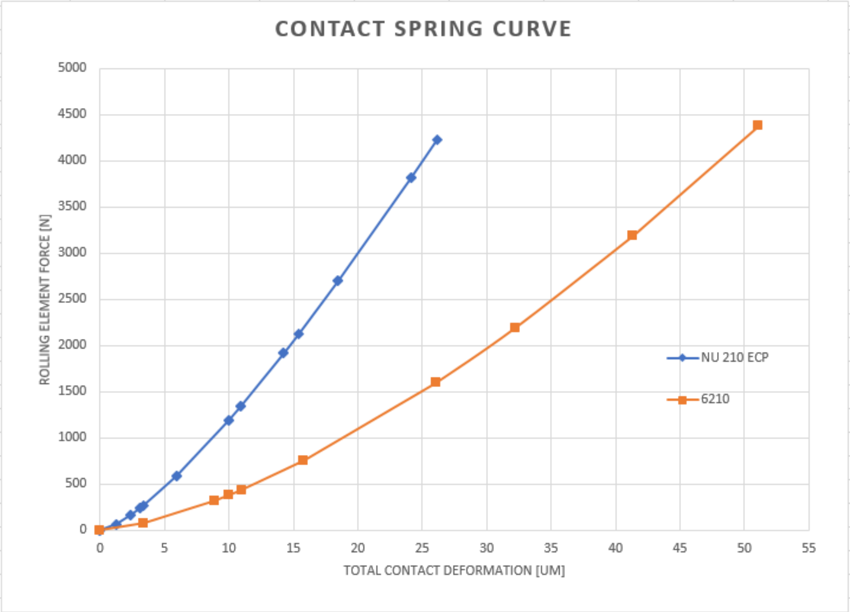


Fig. 10: Bearing contact spring curve for the CRB and DGBB

3.3 Bearing stiffness matrix

A simple shaft-system with a deep groove ball bearing (DGBB 6210, locating bearing) and cylindrical roller bearing (CRB NU 210 ECP, non-locating bearing) is created. Such a model can be made in either SKF SimPro Expert, SKF SimPro Quick or SKF SimPro Spindle. The following input data is used:

- radial force: 16000 N in X-direction in the middle of the shaft (~8000 N on each bearing, to compare with previous examples)
    - Additional load case: 1000 N axial force
- Bearing clearance:
    - 6210: 14.5 um, NU 210 ECP: 45 um
    - Additional case: zero clearance in both bearings
- Rotational speed: 1000 r/min

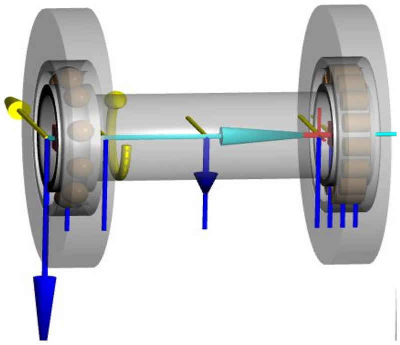
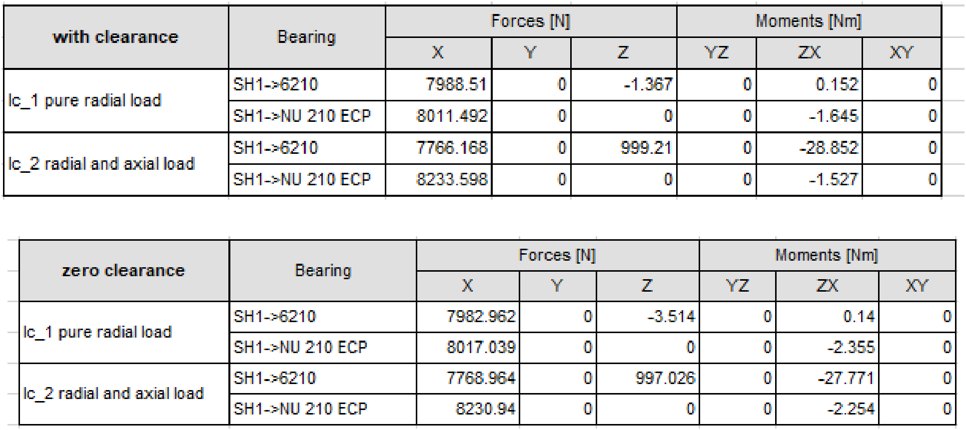


Fig. 11: Shaft system model

Due to the flexibility of the system, the resulting bearing loads (fig. 12) show a slight difference between the left and right bearing. The difference is higher when also an axial force is applied.

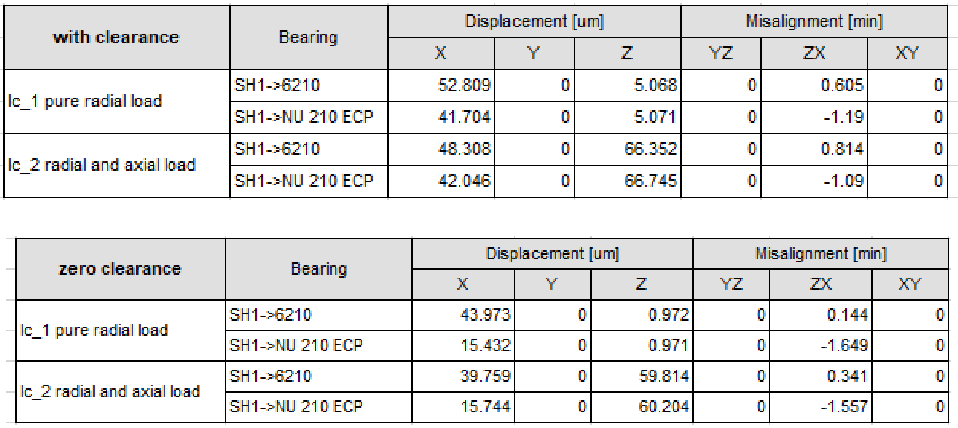


with clearance	Bearing	Forces [N]			Moments [Nm]		
		X	Y	Z	YZ	ZX	XY
lc_1 pure radial load	SH1->6210	7988.51	0	-1.367	0	0.152	0
	SH1->NU 210 ECP	8011.492	0	0	0	-1.645	0
lc_2 radial and axial load	SH1->6210	7766.168	0	999.21	0	-28.852	0
	SH1->NU 210 ECP	8233.598	0	0	0	-1.527	0

zero clearance	Bearing	Forces [N]			Moments [Nm]		
		X	Y	Z	YZ	ZX	XY
lc_1 pure radial load	SH1->6210	7982.962	0	-3.514	0	0.14	0
	SH1->NU 210 ECP	8017.039	0	0	0	-2.355	0
lc_2 radial and axial load	SH1->6210	7768.964	0	997.026	0	-27.771	0
	SH1->NU 210 ECP	8230.94	0	0	0	-2.254	0

Fig. 12: resulting forces and moments, with/without clearance

Besides a radial and axial displacement (fig. 13), also a bearing misalignment occurs which results in a reaction moment on the bearing (fig. 12).



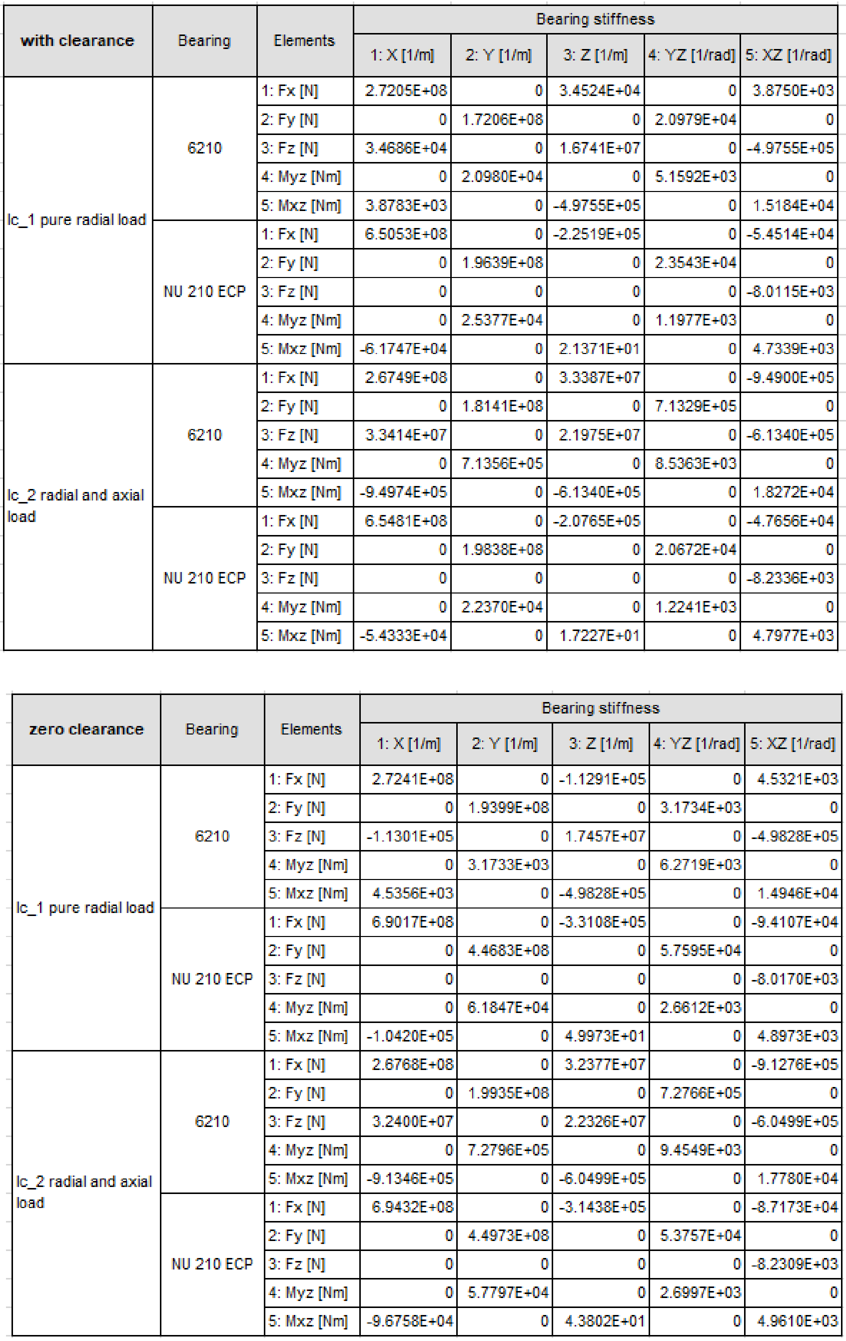
with clearance	Bearing	Displacement [um]			Misalignment [min]		
		X	Y	Z	YZ	ZX	XY
lc_1 pure radial load	SH1->6210	52.809	0	5.068	0	0.605	0
	SH1->NU 210 ECP	41.704	0	5.071	0	-1.19	0
lc_2 radial and axial load	SH1->6210	48.308	0	66.352	0	0.814	0
	SH1->NU 210 ECP	42.046	0	66.745	0	-1.09	0

zero clearance	Bearing	Displacement [um]			Misalignment [min]		
		X	Y	Z	YZ	ZX	XY
lc_1 pure radial load	SH1->6210	43.973	0	0.972	0	0.144	0
	SH1->NU 210 ECP	15.432	0	0.971	0	-1.649	0
lc_2 radial and axial load	SH1->6210	39.759	0	59.814	0	0.341	0
	SH1->NU 210 ECP	15.744	0	60.204	0	-1.557	0

Fig. 13: resulting displacements and misalignments, with/without clearance

The resulting stiffness matrix (fig. 14) is different compared to the one shown in fig. 9 as this stiffness matrix contains more non-zero elements (e.g. element k_{13} or k_{15}). These are non-zero elements due to the misalignment of the bearing.

In addition, the element k_{11} has a different value compared to fig. 8 and 9, both with and without clearance. This shows the influence of misalignment and clearance of the system on the radial stiffness of the bearing.
When an additional axial force is added or the clearance of the bearings is changed, the resulting values will change because the stiffness behaviour of the shaft-bearing-housing system is different. Any variation in the system will change its behaviour and with this also the resulting stiffness matrix of ALL bearings in the system.



with clearance	Bearing	Elements	Bearing stiffness				
			1: X [1/m]	2: Y [1/m]	3: Z [1/m]	4: YZ [1/rad]	5: XZ [1/rad]
lc_1 pure radial load	6210	1: Fx [N]	2.7205E+08	0	3.4524E+04	0	3.8750E+03
		2: Fy [N]	0	1.7206E+08	0	2.0979E+04	0
		3: Fz [N]	3.4686E+04	0	1.6741E+07	0	-4.9755E+05
		4: Myz [Nm]	0	2.0980E+04	0	5.1592E+03	0
		5: Mxz [Nm]	3.8783E+03	0	-4.9755E+05	0	1.5184E+04
	NU 210 ECP	1: Fx [N]	6.5053E+08	0	-2.2519E+05	0	-5.4514E+04
		2: Fy [N]	0	1.9639E+08	0	2.3543E+04	0
		3: Fz [N]	0	0	0	0	-8.0115E+03
		4: Myz [Nm]	0	2.5377E+04	0	1.1977E+03	0
		5: Mxz [Nm]	-6.1747E+04	0	2.1371E+01	0	4.7339E+03
lc_2 radial and axial load	6210	1: Fx [N]	2.6749E+08	0	3.3387E+07	0	-9.4900E+05
		2: Fy [N]	0	1.8141E+08	0	7.1329E+05	0
		3: Fz [N]	3.3414E+07	0	2.1975E+07	0	-6.1340E+05
		4: Myz [Nm]	0	7.1356E+05	0	8.5363E+03	0
		5: Mxz [Nm]	-9.4974E+05	0	-6.1340E+05	0	1.8272E+04
	NU 210 ECP	1: Fx [N]	6.5481E+08	0	-2.0765E+05	0	-4.7656E+04
		2: Fy [N]	0	1.9838E+08	0	2.0672E+04	0
		3: Fz [N]	0	0	0	0	-8.2336E+03
		4: Myz [Nm]	0	2.2370E+04	0	1.2241E+03	0
		5: Mxz [Nm]	-5.4333E+04	0	1.7227E+01	0	4.7977E+03

zero clearance	Bearing	Elements	Bearing stiffness				
			1: X [1/m]	2: Y [1/m]	3: Z [1/m]	4: YZ [1/rad]	5: XZ [1/rad]
lc_1 pure radial load	6210	1: Fx [N]	2.7241E+08	0	-1.1291E+05	0	4.5321E+03
		2: Fy [N]	0	1.9399E+08	0	3.1734E+03	0
		3: Fz [N]	-1.1301E+05	0	1.7457E+07	0	-4.9828E+05
		4: Myz [Nm]	0	3.1733E+03	0	6.2719E+03	0
		5: Mxz [Nm]	4.5356E+03	0	-4.9828E+05	0	1.4946E+04
	NU 210 ECP	1: Fx [N]	6.9017E+08	0	-3.3108E+05	0	-9.4107E+04
		2: Fy [N]	0	4.4683E+08	0	5.7595E+04	0
		3: Fz [N]	0	0	0	0	-8.0170E+03
		4: Myz [Nm]	0	6.1847E+04	0	2.6612E+03	0
		5: Mxz [Nm]	-1.0420E+05	0	4.9973E+01	0	4.8973E+03
lc_2 radial and axial load	6210	1: Fx [N]	2.6768E+08	0	3.2377E+07	0	-9.1276E+05
		2: Fy [N]	0	1.9935E+08	0	7.2766E+05	0
		3: Fz [N]	3.2400E+07	0	2.2326E+07	0	-6.0499E+05
		4: Myz [Nm]	0	7.2796E+05	0	9.4549E+03	0
		5: Mxz [Nm]	-9.1346E+05	0	-6.0499E+05	0	1.7780E+04
	NU 210 ECP	1: Fx [N]	6.9432E+08	0	-3.1438E+05	0	-8.7173E+04
		2: Fy [N]	0	4.4973E+08	0	5.3757E+04	0
		3: Fz [N]	0	0	0	0	-8.2309E+03
		4: Myz [Nm]	0	5.7797E+04	0	2.6997E+03	0
		5: Mxz [Nm]	-9.6758E+04	0	4.3802E+01	0	4.9610E+03

Fig. 14: resulting bearing stiffness matrix, with/without clearance

4. Summary and conclusion

Different methods as well as different boundary conditions and their variation have an influence on the calculated bearing stiffness values. This has also an impact on how well the real bearing behaviour can be predicted.

Before evaluating and using bearing stiffness results, it is crucial to understand what is required from the application and what the user wants to do with it. With this knowledge the right method should be selected.

Bearing spring curve

The bearing spring curve represents the behaviour of the bearing in ONE direction only. For a combined loading, a bearing spring curve is not representative. The bearing spring curve is usually a very rough assumption of the real bearing behaviour.

The method can be applied in simple cases, e.g. in static assessments when the radial and axial load support is separated or the dependency is very low. It could be applicable when the displacement in only one direction is critical and needs to be calculated, e.g. the radial displacement of a shaft to select a bearing seal for pumps, e-motors, etc.

Bearing contact spring curve

The spring curve of the contact represents the behaviour of the rolling element contact of the bearing, not for the complete bearing.

The method can be applied when the loaded zone of the bearing and the stiffness of the surrounding structure should be considered in an FE tool. Rolling elements are replaced by spring elements with a stiffness value from the bearing contact spring curve.

Bearing stiffness matrix

The bearing stiffness matrix represents the behavior of a bearing in all degrees of freedom for ONE specific loading condition. This includes the behavior of the complete bearing-shaft-housing system incorporating operating clearance/preload, misalignments, shaft bending, actual forces and moments and speed effects. Therefore it is recommended to extract the stiffness matrix only from a complete SKF SimPro model (SKF SimPro Expert, SKF SimPro Quick, SKF SimPro Spindle).

This method can be applied in an FE tool in which the bearing is replaced by a single node. This node is then connected to the surrounding part. As property the stiffness matrix is given, which now represents the behavior of the bearing in all DOFs (valid for ONE specific loading condition).