Coupling with adjustable torsional stiffness

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Introduction

Resonance occurs when the frequency of periodically applied force is equal or close to natural frequency of the system. Vibrations caused by resonance effect are more commonly experienced with larger machines, such as paper machines and large generators [1].

A coupling is a device used to mechanically connect two shafts in order to transmit torque (figure 1). The coupling stiffness must be high enough to allow efficient torque transmission, but also the device has to be able to operate under conditions like misalignment which require flexibility. The torsional stiffness of the coupling affects the natural frequencies of the shaft line and it needs to be considered when selecting a coupling.

Typically, the torsional stiffness of the couplings is not adjustable and only few commercial solutions exist. They require disassembly of coupling and changing of parts to adjust the stiffness [2]. Various prototypes of coupling with adjustable torsional stiffness have been made and tested during research in other universities [3],[4]. The goal of this research was to determine the torsional stiffness range of a new coupling design, which has easily adjustable torsional stiffness. The torsional stiffness was determined by using analytical calculations, FEM simulation and practical measurements. Also, torsional vibration tests were made to study if the coupling has the capability to adjust the torsional natural frequencies of a rotating shaft line.

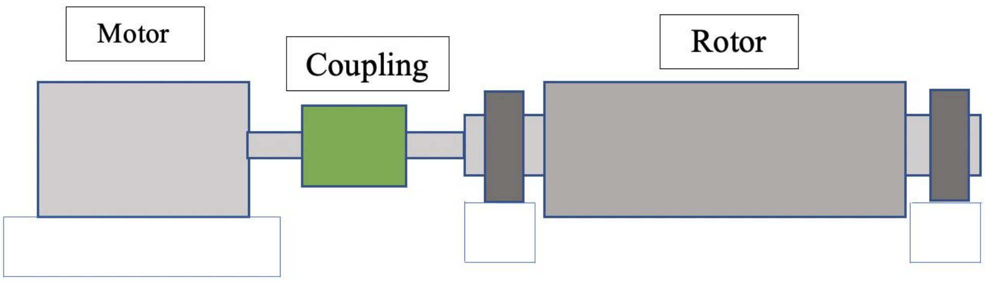

Figure 1. Typical motor-rotor coupling connection.

Methods

Torsional vibration

Torsional vibration is an oscillation of axial rotation between two points in rotating shaft or machine element (figure 2). The vibrations typically manifest when transmitting power, for example in gearboxes or crankshafts. The vibration is excited when torque is applied to a shaft and the shaft twists in radial direction, creating a phase difference in angular displacement between the shaft ends [5].

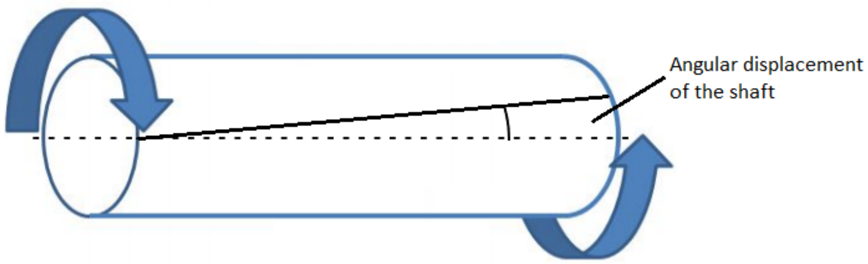

Figure 2. Basic principle of a twisted shaft [6]

Coupling with adjustable torsional stiffness

Figure 3 presents the coupling and the main parts. The coupling consists of input and output halves at the ends, 6 beams, adjustable flange and middle shaft. The shaft of electric motor is attached to the input half. Torque is transferred from the input half through the beams to the adjustable flange. The flange transfers the torque to the middle shaft by spline. The middle shaft is fixed to the output half. The stiffness of the coupling is adjusted by moving the position of the adjustable flange. When the flange is near the input half the stiffness of the coupling is high since the effective length of the beam is short. When the flange is moved towards the output half the effective length of the beams increases and the stiffness decreases.

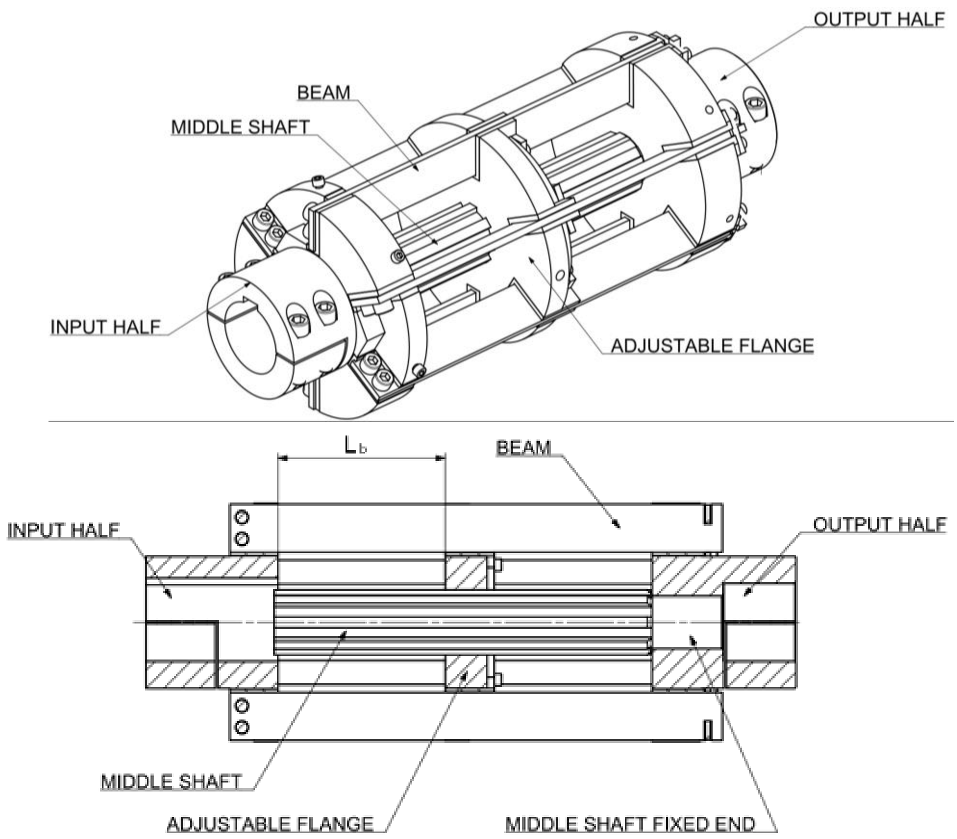

Figure 3. Coupling with adjustable torsional stiffness. L_b represents the effective length of the beams.

Analysis of the coupling with adjustable torsional stiffness

Analytical calculation of torsional stiffness

The coupling consisted of six beams and a spline as shown in figure 3. The beams were parallel, and stiffness of the beams was defined as shown in equation (1) in accordance with [7]. k_b corresponds to the input side of the adjustable flange while k_{bs} corresponds to the output side.

$$k_b = r \cdot 6 \cdot \frac{3EI}{{L_b}^3}, \quad k_{bs} = r \cdot 6 \cdot \frac{3EI}{(L-L_b)^3}. \tag{1}$$

Where L_b is the effective length of the beams, L is the total length of the beams, r is the distance between the center of the beam cross section and the center of the rotation, and E is the Young's modulus of the beams (figure 4). I is the second moment of inertia and it is defined as

$$I = \frac{bh^3}{12}, \tag{2}$$

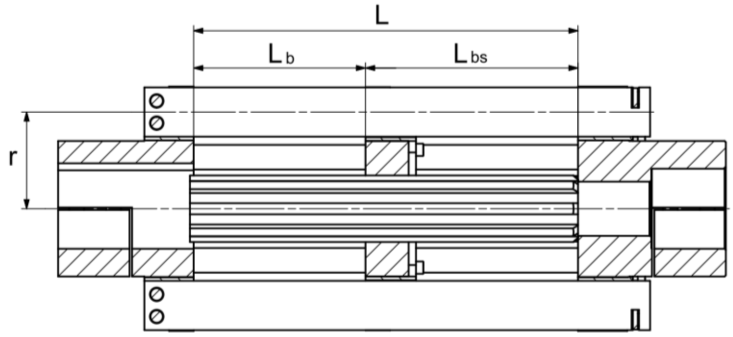

Figure 4. Dimensions used in the calculations.

where b is the width, and h is the height of the cross section of the beam. The stiffness of the shaft is defined in accordance with the torsional rigidity definition

$$k_s = \frac{GI_p}{L-L_b}, \tag{3}$$

where G is shear modulus. I_p is defined as

$$I_p = \frac{\pi d^4}{32}, \tag{4}$$

where d is the average diameter of the spline shaft.
The total stiffness of the coupling is obtained where effective length of the beams was in series with parallel spline shaft and rest of the beams.

$$k = \left(\frac{1}{k_b} + \frac{1}{k_{bs}+k_s}\right)^{-1} \tag{5}$$

The parameters used in the calculations are presented in Table 1. The effective length of the beams was changed in accordance with the adjustable flange position.

Table 1. Geometrical and material parameters used in the calculations.

Parameter	Radius r [mm]	Young's modulus E [GPa]	Shear modulus G [GPa]	Beam height h [mm]	Beam width b [mm]	Total beam length L [mm]	Spline shaft diameter d [mm]
Value	78.6	200	80	40	6	312	50

Simulated torsional stiffness

The coupling stiffness was also calculated using Finite Element Method (FEM). The used model was simplified by removing excess parts and geometry like screws, fillets and spline tooth.

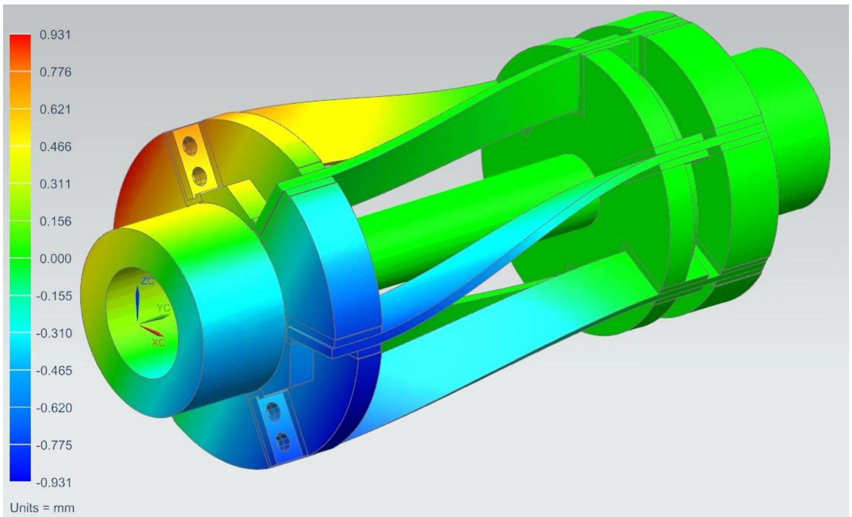

Figure 5. Result of a simulation with the coupling at the lowest stiffness. Deformation is exaggerated.

Experimentally measured torsional stiffness

The rotating angle was measured using a lathe as a test bench (figure 5). The input end of the coupling was attached to the lathe chuck to allow only torsional rotation and the output end was fixed. Torque was applied using weight and a calibrated torque wrench. Angular displacement was measured using a digital indicator.**,** The torsional stiffness was calculated from the measured torque and the angular displacement.

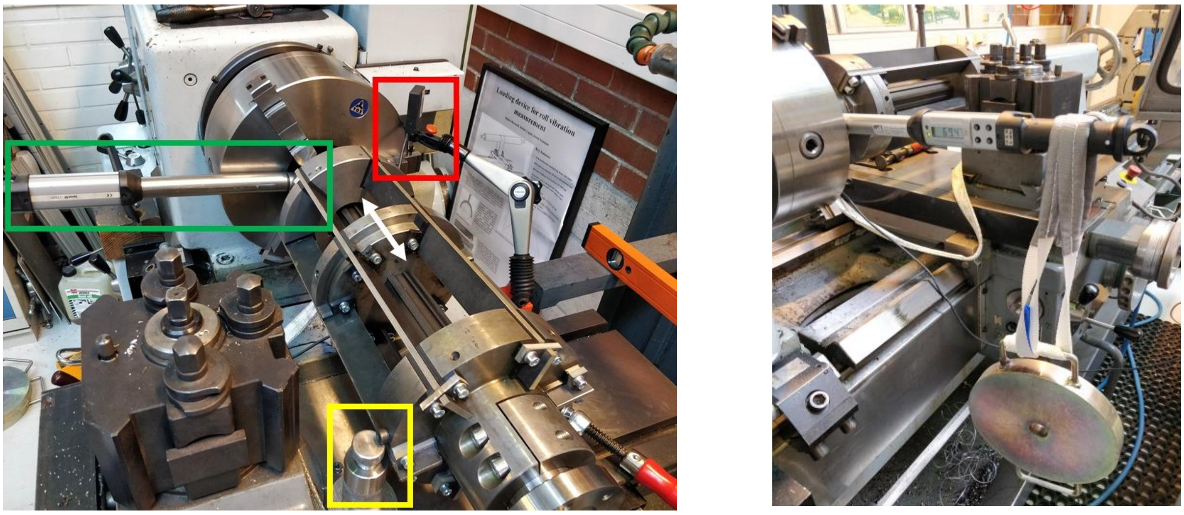

Figure 6. The test rig of the stiffness measurement on the left side (green: torque wrench, red: Indicator measuring displacement, yellow: fixing device, white arrow: stiffness adjustment). On the Right side, torque wrench with a weight.

The measurement process was completed as follows:

1) The adjustable flange was moved to the input end of the coupling, which is the stiffest point
2) Torque was applied, and the rotating angle was measured
3) Adjustable flange was moved towards the output end of the coupling to lower the stiffness
4) Steps 2–3 were repeated until the whole stiffness range of the coupling was measured

Torsional natural frequency analysis

Torsional vibration tests were made to study if the coupling has the capability to adjust the torsional natural frequencies of a rotating shaft line. The test configuration (figure 7) consisted of two electric motors, gearbox, rotor, elastomeric coupling, torque sensor and the coupling with adjustable torsional stiffness.

The driving electric motor with the gearbox was used to rotate the shaft line and the loading electric motor was used to produce torsional vibrations to the system. The elastomeric coupling connected the driving electric motor to the rotor and the coupling with adjustable torsional stiffness connected the loading electric motor to the rotor. Torque sensor was between the rotor and adjustable coupling, which was used to measure the torsional vibrations in the system.

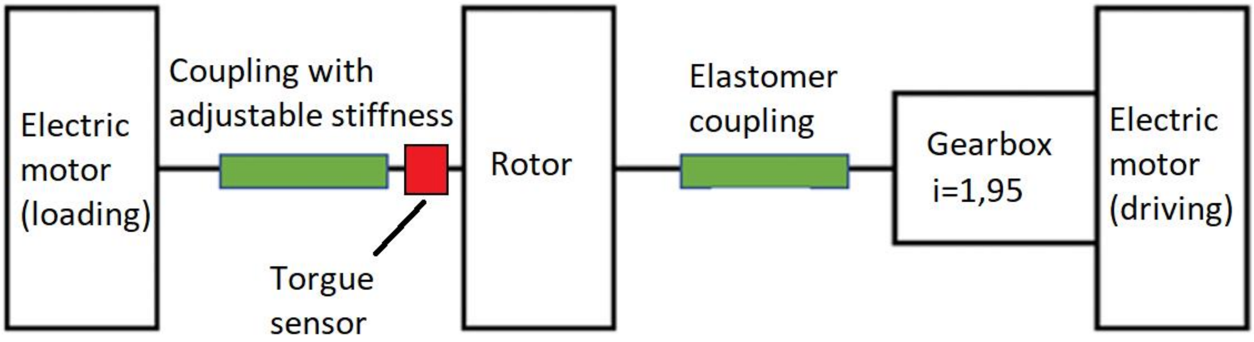

Figure 7.Test configuration for measuring torsional vibrations. From left: loading electric motor, the coupling with adjustable torsional stiffness, torque sensor, elastomeric coupling, gearbox, and driving electric motor.

The torsional vibration measurement process was completed as follows:
1) The adjustable flange was moved to the input end of the coupling, which is the stiffest point
2) Driving electric motor accelerated the shaft line to 10 revolutions per minute and it held the rotation constant
3) The loading electric motor was set to torsionally oscillate the shaft line at 1 Hz.
4) The oscillation torque was measured with the torque sensor
5) Torsional oscillation frequency increased by 0.1 Hz increments
6) The oscillation torque was measured with the torque sensor
7) Steps 5–6 were repeated until the oscillation frequency was 50 Hz
8) Both motors were stopped, and the adjustable flange was moved towards the output end of the coupling to lower the stiffness
9) Steps 3–8 were repeated until the whole stiffness range of the coupling was measured

Results and conclusions

Coupling stiffness

The stiffness of the coupling was determined with analytical, simulated and experimental methods. The determined stiffnesses can be seen as function of the effective length of the beams in figure 6. The results were obtained considering an effective beam length range of 0-260 mm which corresponds to the effective beam length. The measurements were done in 9 adjustable flange positions. The torsional stiffness values are presented in table 2 and table 3.

Table 2. Torsional stiffness values from analytical calculations and FEM simulation as a function of adjustable flange position.

Adjustable flange position	Analytical stiffness	Simulated stiffness	Analytical to simulated stiffness ratio
[mm]	[Nm/rad]	[Nm/rad]	
0	157837	165450	95%
26	169129	142142	119%
57	163831	87259	188%
101	106887	39362	271%
151	45141	18000	250%
206	22188	11281	197%
260	11450	7670	149%

The measured stiffness values were much lower compared to the simulations (table 3).

Table 3. Measured stiffness values and comparison to simulated stiffness values.

Adjustable flange position	Measured stiffness	Simulated stiffness	Measured to simulated stiffness ratio
[mm]	[Nm/rad]	[Nm/rad]	
0	45716	165450	28%
26	37590	142142	26%
57	27068	87259	31%
101	17045	39362	43%
151	11491	18000	63%
206	7969	11281	70%
260	6424	7670	80%

The torsional stiffness decreases when the effective length L_b is increased (figure 8). The stiffness curve from analytical calculations and the FEM simulation are similar, but the curve from the analytical calculations has a larger slope and the stiffness is generally higher. The difference is likely caused by the analytical calculations being simplified. The formula used considers the force to be applied evenly to the beam. However, the torque load creates uneven loading to the beam surface, which also causes the beams to twist.

The measured torsional stiffness was much lower than simulated and calculated values, especially in the higher stiffness range. The phenomenon was deduced to be a caused by inaccuracies in the simulation and the measurement setup. The measurements should have been done in a proper measurement rig instead of the lathe.

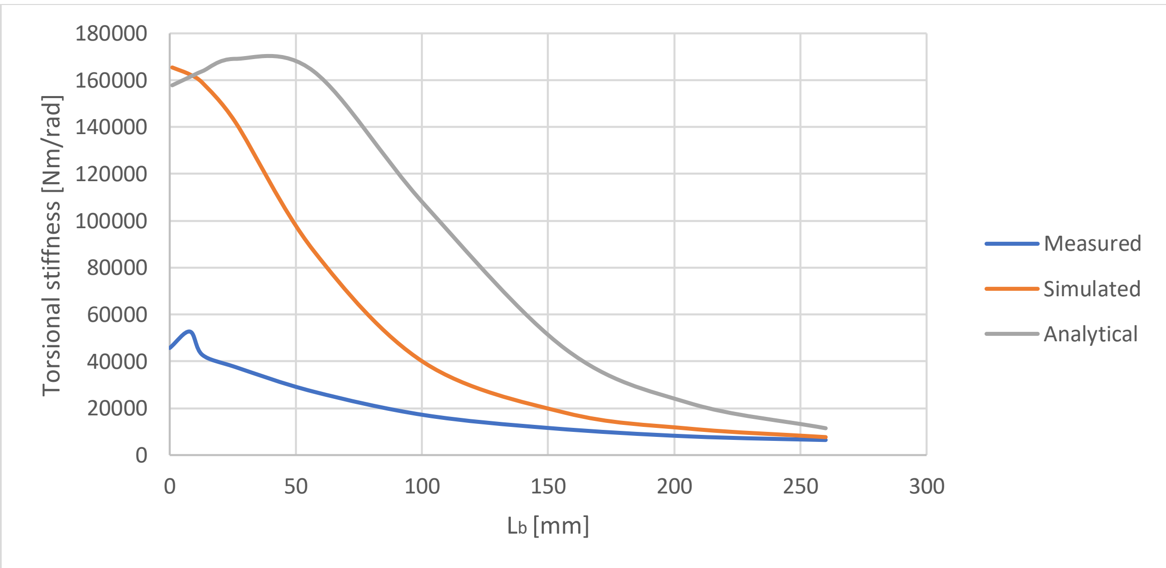

Figure 8. Analytical, simulated and experimental results of the coupling stiffness

Torsional natural frequencies

Torsional vibration tests were made to study if the coupling has the capability to adjust the torsional natural frequencies of a rotating system. As a result of the tests, the torsional natural frequency increased from approximately 15 Hz to 45 Hz when the torsional stiffness was adjusted. The measurement results are presented in figure 9. The figure presents measurements from 7 tests with different adjustable flange positions.

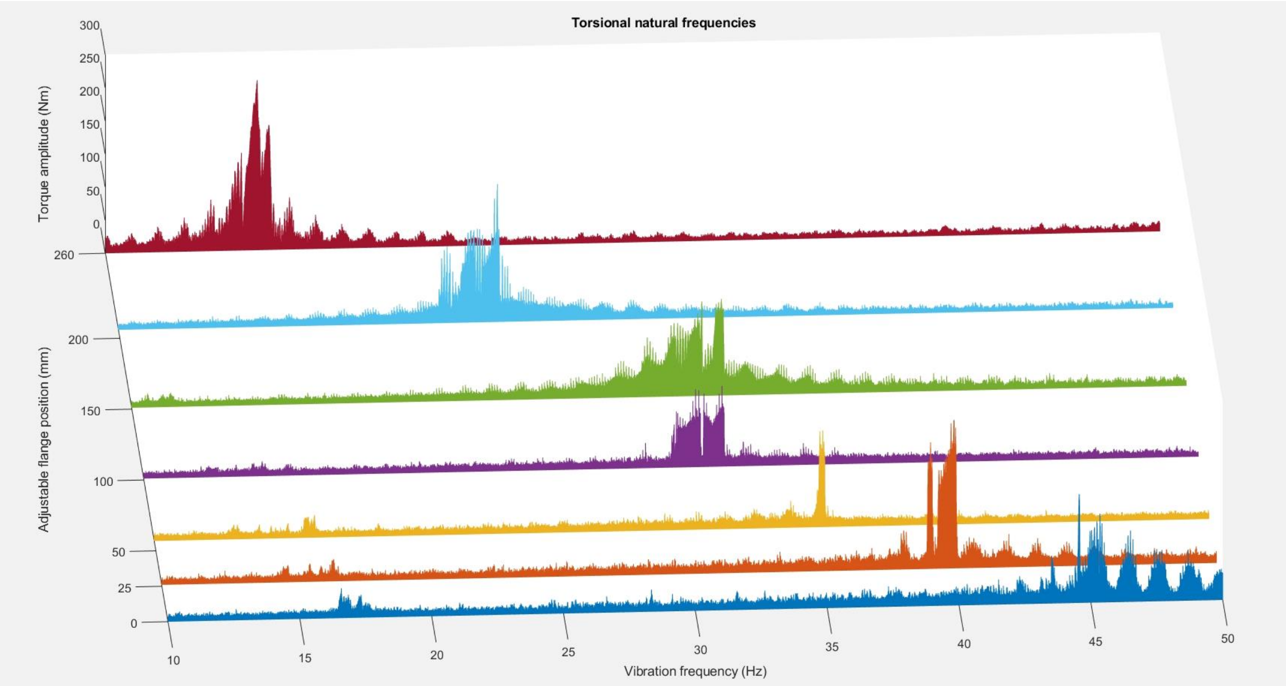

Figure 9. The measurement results from the vibration tests. The torsional natural frequency increases as the adjustable flange position decreases.

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