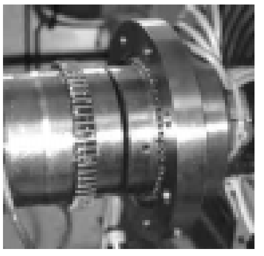
Laborelec

Reactions of flexible bearings and vibrations.



In collaboration with

References

These are a few textbooks and papers dealing with flexible couplings.

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Mancuso J.R.: Couplings and Joints, Design, Selection and Applications, Marcel Dekker New Yprk, Basel, 1986.

South D.W. and J.R.Mancuso: Mechanical Power Transmission Components,Marcel Dekker, New York, Basel, 1994

Neale M., P. Needham and R. Horrell "Couplings and Shaft Alignment" Mechanical Engineering Publication, London,

Piotrowski, J: Shaft Alignment Handbook, Marcel Dekker, New York, Basel, 1986.

Godin, A, Esco Transmission. (very helpful, handed out his references)
Tel 02 720 48 80 Fax 02 721 28 27

Randiranarivo, EDF. (mentioned that EDF switched from gear to disk couplings)
Tel 00 33 1 30 87 79

Watremez JM et Faure, Compagnie Messiaen et Durand, (now retired)
Tel 00 33 27 73 53 03 Fax 00 33 27 78 36 09

Heyer,R. and W.Möllers : "RückstellKräfte und -momente nachgiebiger Kuppplungen bei Wellen-verlagerungen", Antriebstechnik 26 (1987) Nr.5 (Research in THU Bochum).

Yanpol'skii et al: "Formation of disturbing forces in toothed clutches" Russian Engineering Journal , volume LV No 10, translated from Vestnik Mashinostroeniya, vol 55, issue 10, 1975, pp.12-15.

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Why worry about flexible couplings? (partly adapted from Mancuso)

Flexible couplings are a vital part of a mechanical power transmission system. Unfortunately, many system designers treat flexible couplings as if they were a piece of hardware.

The amount of time spent in selecting a coupling and determining how it interacts with a system should be a function not only of the cost of the equipment but also how much downtime it will take to replace the coupling or repair a failure. In some cases the process may take only a little time and be based on past experience; however, on sophisticated systems this may take complex calculations, computer modeling, and possibly even testing. A system designer or coupling user just cannot put any flexible coupling into a system with the hope that it will work. It is the system designer or the user's responsibility to select a coupling that will be compatible with the system.

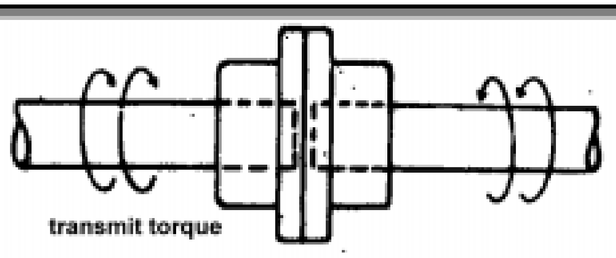
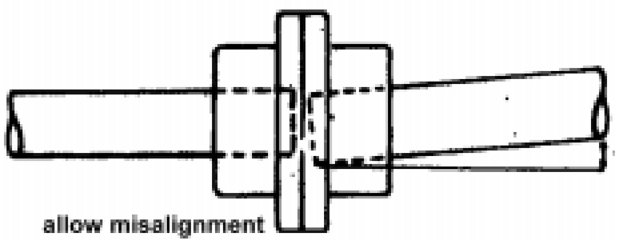
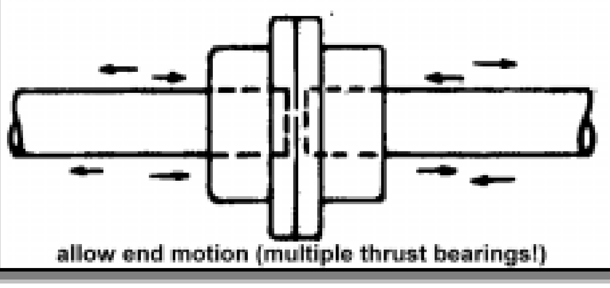
Flexible coupling manufacturers are not usually system designers; rather, they size, design, and manufacture couplings to fulfil the requirements supplied to them. Some coupling manufacturers can offer some assistance based on past exposure and experience. They are the experts in the design of flexible couplings, and they use their know-how in design, materials, and manufacturing to supply a standard coupling or a custom-built one if requirements so dictate. A flexible coupling is usually the least expensive major component of a rotating system. It usually costs less than **1%,** and probably never exceeds 10%, of the total system cost. And yet it can cause severe financial losses when nor well selected and operated

Flexible couplings are called upon to accommodate for the calculated loads and forces imposed on them by the equipment and their support structures. Some of these are motions due to thermal growth deflection of structures due to temperature, torque-load variations, and many other conditions. In operation, flexible couplings are sometimes called on to accommodate for the unexpected. Sometimes these may be the forgotten conditions or the conditions unleashed when the coupling interacts with the system, and this may precipitate coupling or system problems. It is the coupling selector's responsibility to review the interaction of the coupling with that system. When the coupling's interaction with the system is forgotten in the selection process, coupling life could be shortened during operation or a costly failure of coupling or equipment may occur.

In this research, one not only deals with static reactions developed by flexible couplings (these have been known for a while) but also with the time-varying reactions causing vibrations. This is much less known and required special rigs and measurement setups. This approach identifies which amongst the most popular flexible bearings are the least prone to generate vibrations.

What are flexible couplings (partly borrowed from Mancuso)

Historically, rotating equipment was first connected by means of rigid flanges Experience indicated that this method did not accommodate the motions and excursions experienced by the equipment. One then tried to thin these flanges and allow them to flex. Rigid couplings are used to connect equipment that experiences very small shaft excursions or with shafts made long and slender enough so that they can accept the forces and moments produced from the flexing flanges and shafts (think of STEGs in Electrabel between generator and compressor).

<table>
<tr><th colspan="2">The Three functions of a flexible couplings</th></tr>
<tr><td></td><td>Fair enough. They must transmit power. The maximum rotational speed at which they operate is important when selecting a flexible coupling.</td></tr>
<tr><td></td><td>Subsequent motion of bearings and/or foundations may cause misalignment. The latter should remain within the limits prescribed by manufacturers for the selected coupling.
This is the basic function of flexible vs. rigid couplings.</td></tr>
<tr><td></td><td>Very important when thrust bearings come into conflict with rigid couplings.
Germans consider this as axial misalignment.
ULB test rigs have not focused on "axial misalignment".</td></tr>
</table>

Efficiency in Power Transmission

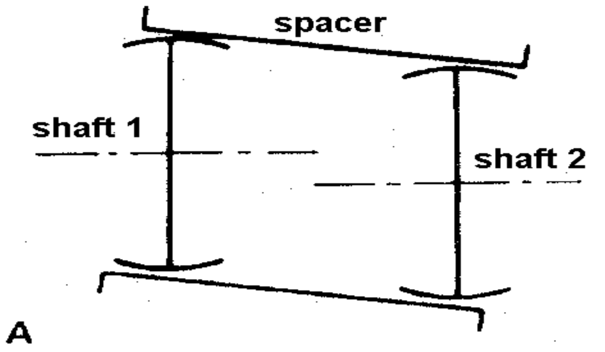
Flexible couplings must couple two pieces of rotating equipment, equipment with shafts, flanges, or both. These interface connections are numerous.

Flexible couplings must also transmit power efficiently. Usually, the power lost by a flexible coupling is small, although some couplings are more efficient than others. Power is lost in friction heat from the sliding and rolling of flexing parts and at high speed, windage and frictional losses indirectly cause lost efficiency.

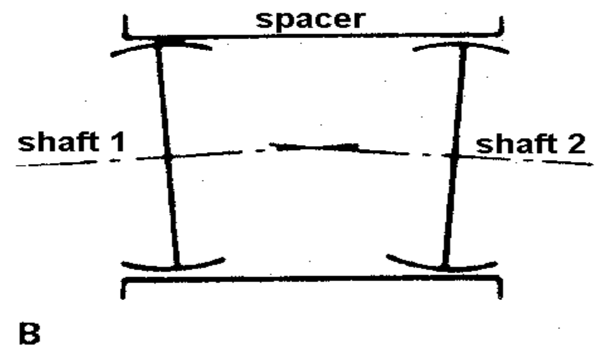
Most flexible couplings are better than 99% efficient.

How flexible couplings accommodate Misalignment.

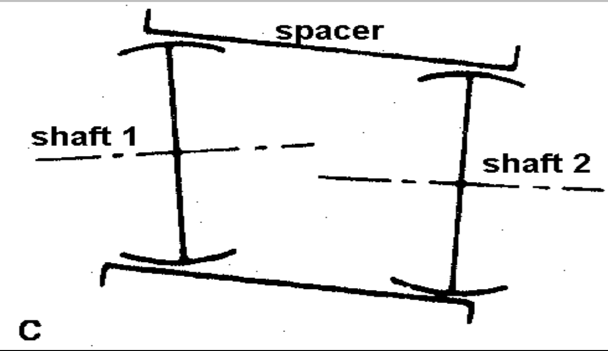
Flexible couplings must accommodate three types of misalignment:



Parallel offset: Axes of connected shafts are parallel but not in the same straight line. One also calls it **radial misalignment** later in the text.



Angular: Axes of shafts intersect at the center point of the coupling, but not in the same straight line.



Combined angular and *offset (radial)*: Axes of shafts do not intersect at the center point of the coupling and are not parallel.

Flexible couplings in operation

Most flexible couplings are designed to accommodate axial movement of equipment or shaft ends. In some cases (e.g., motors) couplings are required to limit axial float of the equipment shaft to prevent internal rubbing of a rotating part within its case.

Accommodation of misalignment and end movement must be done without inducing abnormal loads in the connecting equipment. Generally, machines are set up at installation quite accurately. There are many things that force equipment to run out of alignment. The thermal effects of handling hot and cold fluids cause some movement in the vertical and axial direction, together with differentials of temperature in driver media such as gas and steam. The vertical motions could be a result of support structure expansions due to temperature differences, distortion due to solar heating, axial growth or a combination of these. Horizontal motions are usually caused by piping forces or other structural movements, temperature differentials caused by poor installation practices, and expansions or contractions caused by changes in temperature or pressure differentials of the media in the system.

It is a fact of life that machinery appears to live and breathe, move, grow, and change form and position; this is the reason for using flexible couplings. A flexible coupling is not the solution to all movement problems that can or could exist in a sloppy system. Using a flexible coupling in the hope that it will compensate for any and all motion is naive. Flexible couplings have their limitations. The equipment or system designer must make calculations that will give a reasonable estimate of the outer boundaries of the anticipated gyrations. Unless those boundaries are defined, the equipment and system designer may just be transferring equipment failure into coupling failure.

What is known about flexible coupling reactions

One thing to remember is that when subjected to misalignment and torque, all couplings react on connected equipment components. Some produce greater reactionary forces than others and if overlooked, can cause shaft failures, bearing failures, and other failures of equipment components. They may also excite vibrations with time-varying reactions. This last point has received less attention in the technical literature.

Rigid couplings produce the greatest reactions.

1. Mechanically flexible couplings such as gear, chain, and grid couplings produce high to moderate moments and forces on equipment that are a function of torque and misalignment.

2. Elastomeric couplings produce moderate to low moments and forces that are slightly dependent on torque.

3. Metallic membrane couplings produce relatively low moments and forces which are relatively independent of torque.

The most commonly used flexible couplings today are those that produce the greatest flexibility (misalignment and axial capacity) while producing the lowest external loads on equipment.

In the present research, one compares flexible couplings of the first three types (gear,

elastomeric and disk) in terms of

1. **Static reactions in presence of misalignment and torque: these reactions reflect on the loads of mainly the nearest bearings. The present research also investigates the relationship between the directions of static reaction and misalignment.**
2. **Dynamic reactions in presence of misalignment and torque: these reactions cause vibrations. These reactions have never been precisely stated in the technical literature.**

Types and inner workings of couplings

There are many types of couplings. They can virtually all be put into two classes, two disciplines, and four categories. The two classes of couplings are:

1. The rigid coupling
2. The flexible coupling

The two disciplines for the application of flexible couplings are:

(a) The miniature discipline, which covers couplings used for office machines, servomechanisms, instrumentation, light machinery, and so on).
(b) The industrial discipline, which covers couplings used In the steel industry, the petrochemical industry, **utilities**, off-road vehicles, heavy machinery, and so on. Therefore, one does not focus upon universal joints.

In this research we deal exclusively with industrial couplings.

The four basic categories of flexible industrial couplings are:

1. Mechanically flexible couplings
2. Elastomeric couplings
3. Metallic membrane couplings
4. Miscellaneous couplings

The general operating principles of the four basic categories of industrial couplings are as follows:

1. **Mechanically *flexible couplings*:** In general, these couplings obtain their flexibility from loose-fitting parts and/or rolling or sliding of mating parts. Therefore, they **usually require lubrication** unless one moving part is made of a material that supplies its own lubrication needs (e.g., a nylon gear coupling). Also included in this category are couplings that use a combination of loose-fitting parts and/or rolling or sliding, with some flexure of material.

2. **Elastomeric couplings**: In general, these couplings obtain their **flexibility from stretching or compressing a resilient material** (rubber, plastic, etc.). Some sliding or rolling may take place, but it is usually minimal.

3. ***Metallic* membrane couplings**: In general, the flexibility of these couplings is obtained from the **flexing of thin metallic disks or diaphragms**.

4. **Miscellaneous couplings**: These couplings obtain their flexibility from a combination of the mechanisms described above or through a unique mechanism like spring couplings

Gallery of flexible couplings

Yellowed boxes indicate which coupling types were tested in the present research.

Miniature couplings

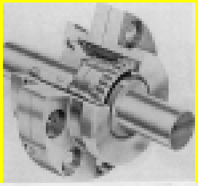
As a refresher, since they are not part of the research.

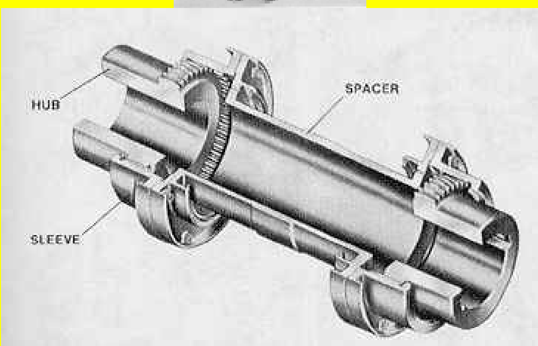
Well-known in such applications as incremental encoders, etc.

Elastomeric like used in the original Bently Nevada rotor kit. Provides some damping.

Mechanically flexible couplings

Gear (TAK, Escogear, Flexident, etc.)

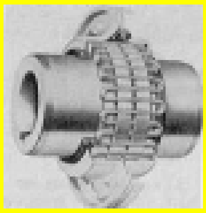




Very popular in high-power applications because of compact design. Semi-flexible for high torques. Lubrication is an issue. Piloting may cause unbalances.

Extensive tests in research

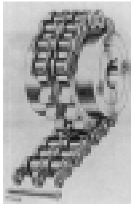
Grid coupling ("Citroën", Flexacier, etc.)



Same remarks as for gear, except that
- Less rigid in torsion
- Piloting less crucial
- Grid segments may excite higher harmonics (4 1/4 grids excite 100 Hz at 1500 rpm Doel III) tested in research

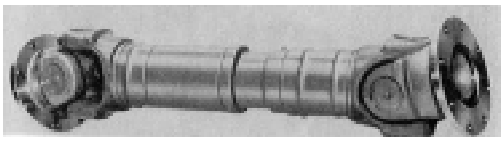
Severe misalignment can cause grid to cut through cover.

Chain couplings



No comment. Pins traversing both chains ensure torque transmission.

Universal joint (automotive, etc..)

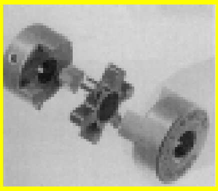


Known to accommodate high misalignments like in automotive applications. May cause vibrations.

Elastomeric couplings

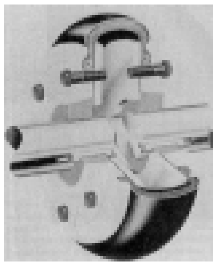
Beware of overheating due to material losses through hysteresis. Beware of chemical agents and material ageing. Lesser ratings.

Blocks (jaws)



Tested in research. Static reactions between disk and gear couplings. Less rigid in torsion.

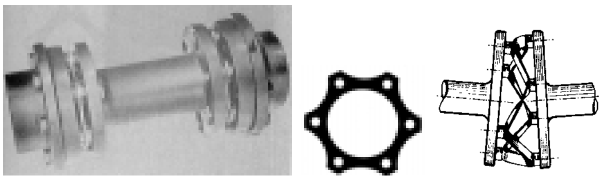
Tire type.



Less rigid in torsion.

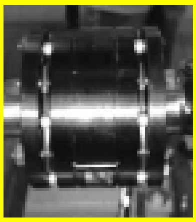
Metallic membrane couplings

Disc



Hub anchors hexagonal flexible disk in three points while the other three interlaced points are anchored on spacer. Ditto on the other side of the spacer. Long spacer here to accommodate higher misalignment grades to avoid excessive disk flexing. Length of pacer is no cure to axial misalignment.

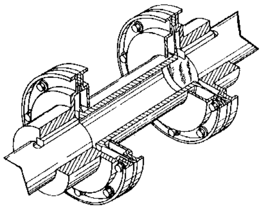
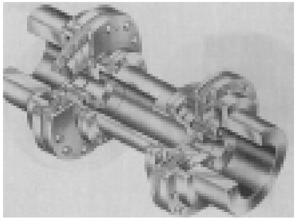
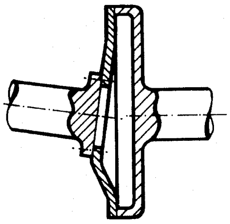
More compact (ESCODISK tested in lab)



No lubrication, no piloting causing unbalances. Lab tests show no dynamic reactions causing vibrations even at the third of sixth harmonic of the rotational speed despite quasi hexagonal shape of flexible disks. For the same rating less compact than gear couplings. Misalignment can be checked from the shape of flexed disks.

Tested in research.

Diaphragm couplings

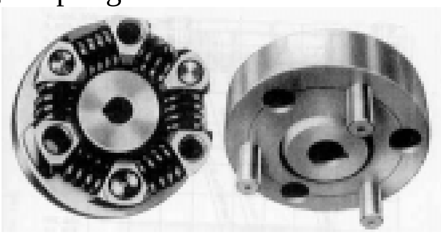




More bending resistance than in disks. Theoretically would not cause higher harmonic excitation than disks since the flexible elements are not anchored in a limited number of points.

Other couplings

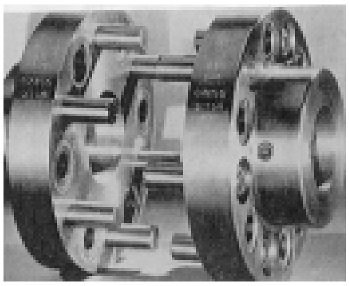
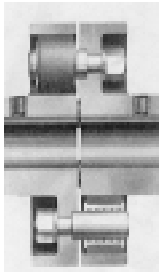
Quite a variety.

Spring couplings



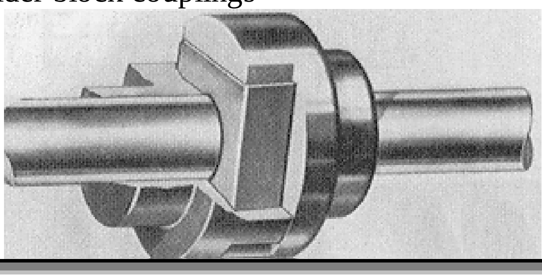
Quite flexible in torsion.

Pin and bush

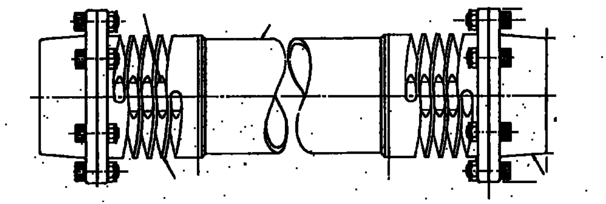



The elastomer sleeve takes over the role of disks and diaphragms without comparable torsional rigidity.

Slider block couplings



Spiral spring coupling



How flexible are gear couplings?

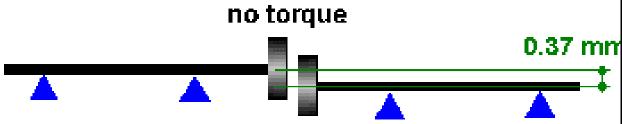
Ideally one would like such couplings to transmit torque and only torque from one shaft end to another without adding either shear reactions or bending moments. These reactions can be either static or dynamic.

This research provides some insight how flexible couplings contribute to vibrations and bearing loads. It focuses on gear couplings (type TAK), but also examines competitors like disk and elastomeric couplings.

Static reactions

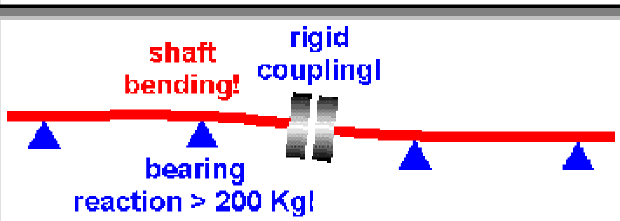
Static reactions of flexible couplings may over- or unload nearby bearings whose selection is often based on the weight of the rotor they support. It may happen that the static reaction of a flexible coupling nears the value of the rotor weight!

Never think that gear couplings do not react on the shaft lines they connect! This is illustrated below for increasing torques and a large misalignment



From experimental rig.

You may align shaft ends properly at first. Due to foundation sagging, it may happen that one gets a rather severe radial misalignment. You can measure it at light loads via such standard methods as the reverse dial or with more advanced methods like OPTALIGN.



From experimental rig.

Trouble is when the torque transmitted by the gear coupling increases to the coupling nominal rating. See what happens! At high values of torque, the gear coupling behaves like a rigid coupling. It bends the shaft ends to bring them in line and causes extra bearing loads. Is that the kind of flexible coupling one generally thinks of?

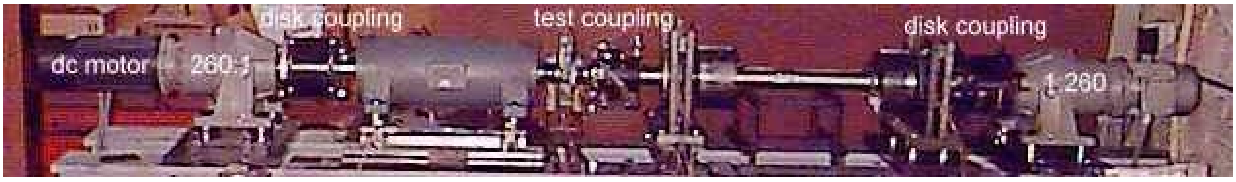
Dynamic reactions

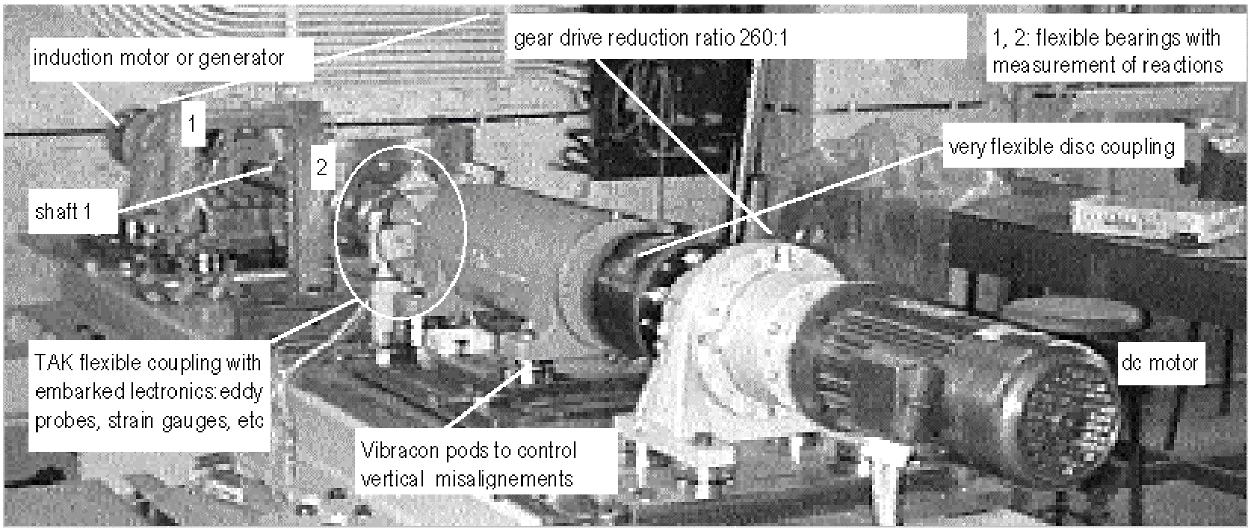
Dynamic reactions from flexible couplings cause vibrations. The most common cause for vibrations originates from rotor unbalances. Balancing norms specify the amount of residual unbalance that is admissible on rotors. These depend on specific balancing grades for different types of applications, the rotor weight and maximum rotational speed.

To a given admissible residual unbalance corresponds a centrifugal force. The dynamic reactions of the couplings become a nuisance when they exceed the contribution of these centrifugal forces.

This is shown to be the case with gear couplings, much less with other types of couplings like disc and elastomeric one.

Test rig for flexible couplings





Flexible couplings like gear and grid ones that rely on sliding surfaces to accommodate misalignment exhibit torque-dependent reactions. Therefore, the rig must be able to produce torques in the range of the coupling nominal values.

At high speeds this corresponds to huge power transfers. The power delivered by the coupling is indeed the product of the torque transmitted and the rotational speed in rad/sec. Assume one wants to transmit a 1600 NXM torque at 1500 rpm. You need ca 250 KW motors. The rig is then costly.

At lower speeds, one can recover huge torques from faster-rotating motors through reductors. In the test rig above, back-to-back 1.1 KW electrical motors rotating at roughly 1500 rpm with 1.1 kW power ratings and connected to the input shafts of 260:1 reductors can produce 1800 NXM at the level of the gear coupling being tested. At the coupling level, the rotational speed is approximately 5.7 rpm. It can vary around this value depending on the slip of the induction motor that depends on the power it delivers or retrieves.

Such an approach has many advantages and one drawback.

The advantages are:

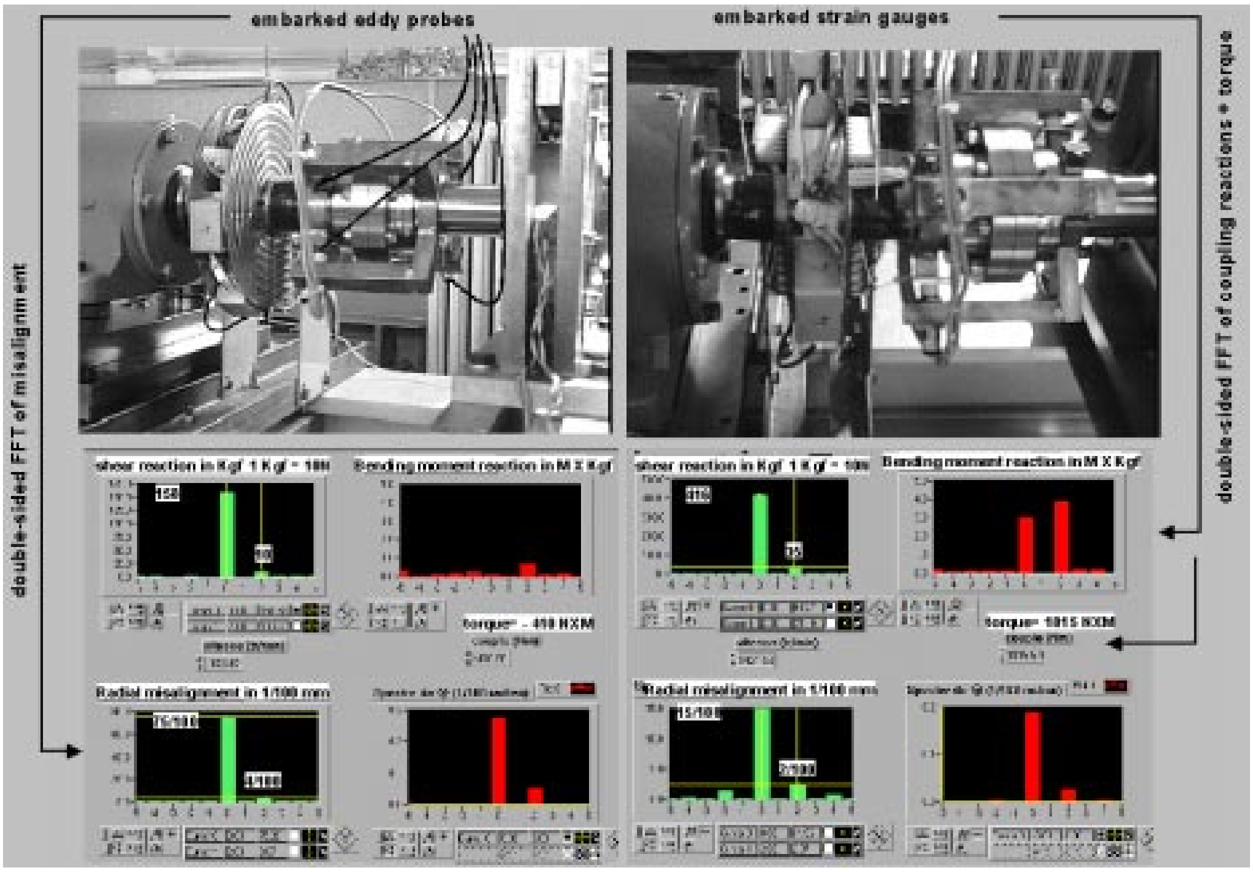
- **lower electrical powers to handle and thus reduced expenses.**
- **one can afford embarking lots of sensors like strain gauges on shaft ends and proximity sensors playing the role of electronic clocks. Slip ring contacts can power these sensors and retrieve their signals without expensive multi-channel telemetry systems.**
- **measuring strains on shaft ends unambiguously yields the coupling reactions.**
- **proximity sensors unambiguously measure on-line misalignments of the shaft ends**

near the coupling, both its static component and its variations.

- one need not bother about reactions caused by high centrifugal forces and thus focus on the reactions of the coupling alone.

The drawback is the oil films may not get renewed as well as at higher speeds. This concerns only flexible couplings relying on lubricants. This could somewhat influence coupling reactions via somewhat higher friction coefficients between teeth. To this aim, tests were conducted on the low-speed test rig with EHP greases, which basically yielded the same reactions.

Measuring coupling misalignments and reactions in real-time on the rig.



Top left: Measurement setup to get misalignment from embarked eddy probes acting like electronic clocks in reverse dial method.
Top right: embarked strain gauges with conditioning to measure bending moment along the shaft end and finally coupling reactions.

All embarked sensors (5 strain gauge bridge amplifiers and 4 eddy probes are powered via the slip rings. The same slip rings transmit the signals back to a National AT MIO E-10 data acquisition card. A phase reference one top/rev synchronizes the measurements on the card to track the angular position of the shaft at all instants, assuming (true here) that the

speed does not vary during a revolution.

Bottom: the type of analysis of signals typically used in this report. More on this below.

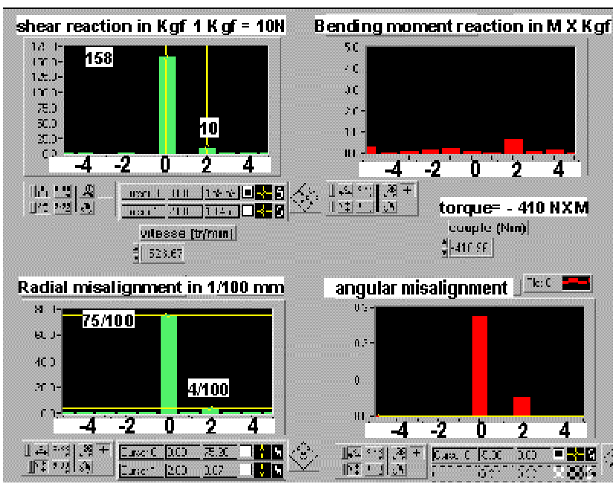
Types of analyses

Frequency analysis of coupling reactions: shear and bending moment and ditto for misalignment: radial and angular, as shown in the diagrams below. How to interpret them them?

The abscissa is graduated from -5 to 5. When a bar-graph shows a big values at, say +2, for the shear (radial) reaction of the coupling, then this reaction (and resulting bearing load) is important and rotate at twice the rotational frequency in the same direction as the shaft revolutions. If this happens at -2, it tells that it rotates counter the shaft at twice its frequency. At zero abscissa, one gets the static reactions and misalignments.

Spectra are obtained for two different values of the torque transmitted by the gear coupling. These are shown in these so-called double-sided (full in Bently Nevada terminology) frequency spectra for two different values of the torques

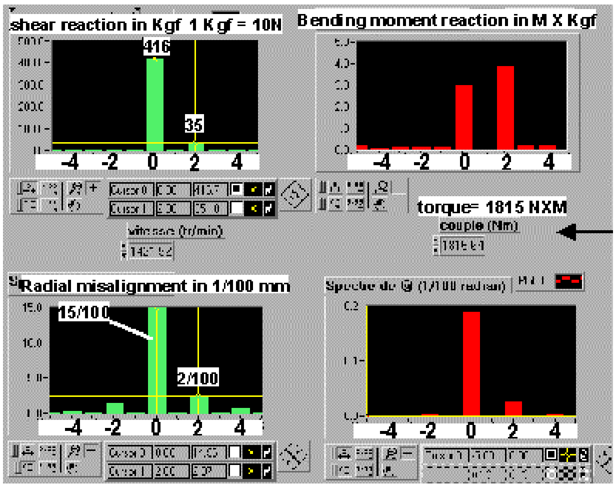
At full torque, the dc (static) contribution amounts to 416 KgF or 4160 N.
There is also a significant 35 KgF or 350 N contribution at the harmonic +2 of the rotational frequency. This corresponds to a force rotating in the same direction as the shaft at double the speed thereof. Testing another gear coupling with mixes of torques and misalignments confirms this trend. Based on two types of gear couplings (FEXIDENT and ESCOGEAR) one can thus claim there is very little hope that radial vibrations caused by these reactions could indicate in which directions the misalignment occurs.
Results can be compared below where the reaction is somewhat higher due to an initially larger radial misalignment at no load.



The initial coupling misalignment is rather severe: ca 75/100 mm radial and small angular.

At small torque values (reverse -410 N X M), one retrieves these values with a small variation at twice the shaft rev in the direction of shaft revs.

The static radial reaction is 158 daN and 10 daN at H+2. They would be almost zero at zero torque.



At full torque, the dc (static) contribution amounts to 416 KgF or 4160 N! Not pleasant for bearings…

At the same time, the radial misalignment at the coupling level almost vanishes. Shaft ends bend as monitored by strain gauges. The coupling has become rigid!!

There is also a significant 35 KgF or 350 N contribution at the harmonic +2 of the rotational frequency. This corresponds to a force rotating in the same direction as the shaft at double the speed thereof. All subsequent tests confirm this. There thus little hope that radial vibrations caused by these reactions would indicate in which direction a misalignment occurs.

One has performed these analyses for all types of misalignments and torques on two different gear couplings: FLEXIDENT and ESCOGEAR with basically the same results and the same conclusion as above: vibrations is of no help to locate the direction of the misalignment.

Before moving to the summary of these results, here is again another virtual instrument to understand the situation. It features special data processing techniques involving full FFT of "strain orbits" obtained from embarked strain gauges as well as "misalignment orbits" reconstructed from embarked electronic clocks (eddy probes).

The Theorist's corner (not to display on the web page)

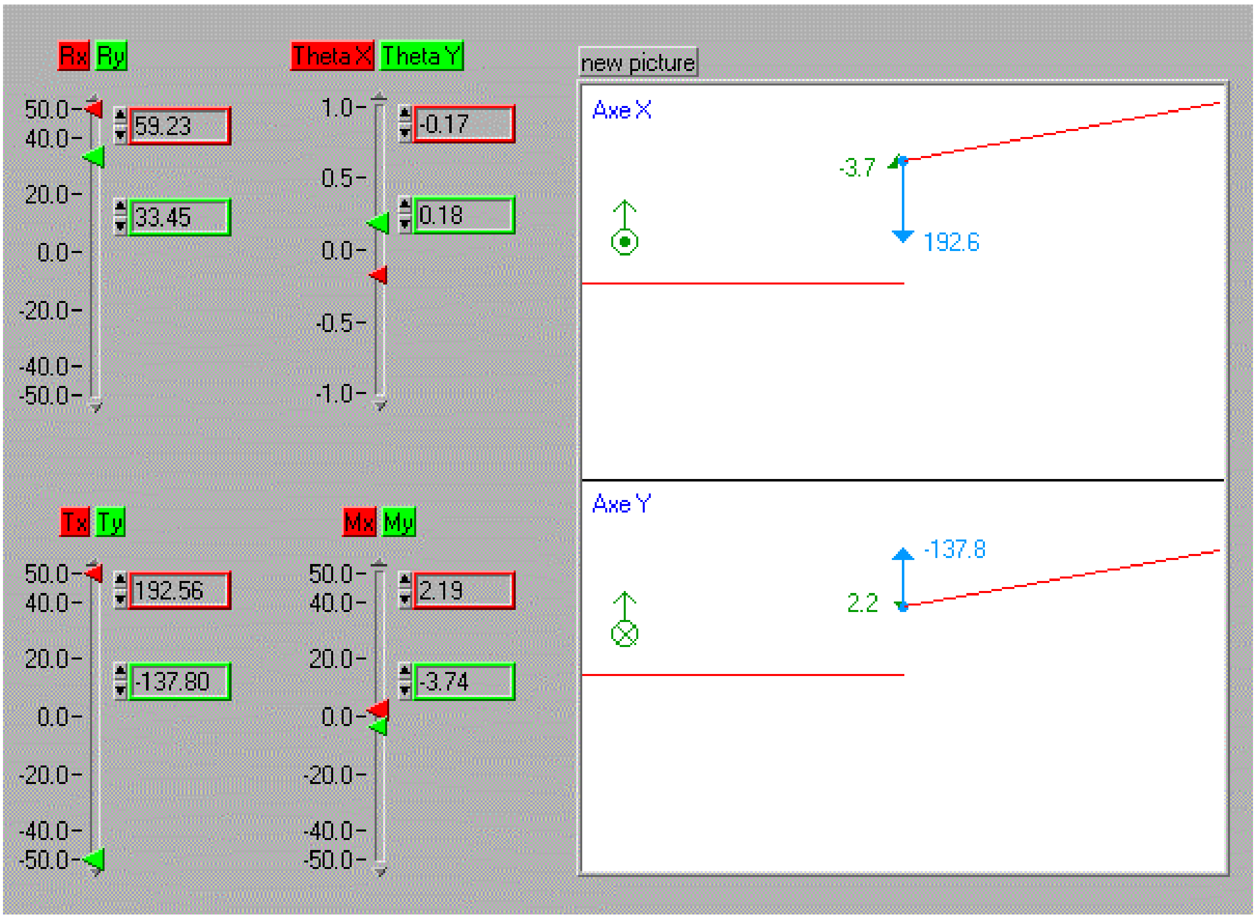
For data processing buffs, this kind of analysis is rather elegant. In two different cross-sections of an overhung shaft end next to the coupling, one installs pairs of embarked strain gauges measuring bending in two perpendicular directions thus rotating with the shaft. At time zero these directions coincide with the horizontal and vertical respectively. One performs the sampling at equal rotation interval over a shaft rev or a power of 2 number of revs. Then one combines the bridges responses as "strain orbits" to which one applies double-sided Fourier Transform. Quite a twisted way to use these! Then one applies the conventional material strength equations of beams (overhung shaft ends are none others than rotating beams) to these double-sided Fourier Transforms in order to retrieve the coupling reactions spatially and in the frequency domain. This requires a simple coordinate transform from a rotating to a fixed coordinates in space.
In the same vein, one can decompose local misalignment spatially and in the frequency domain by carefully examining the kinematics of the reverse dial method and what it corresponds to in terms of the clock readings mimicked by the embarked eddy probes..

There is a report with all equations available that mix motion, material strength and spatial-frequency analyses.

Measured gear coupling reactions and local misalignments

The following virtual instruments visualize in real-time what happens when applying an increasing torque applied to a misaligned gear coupling.

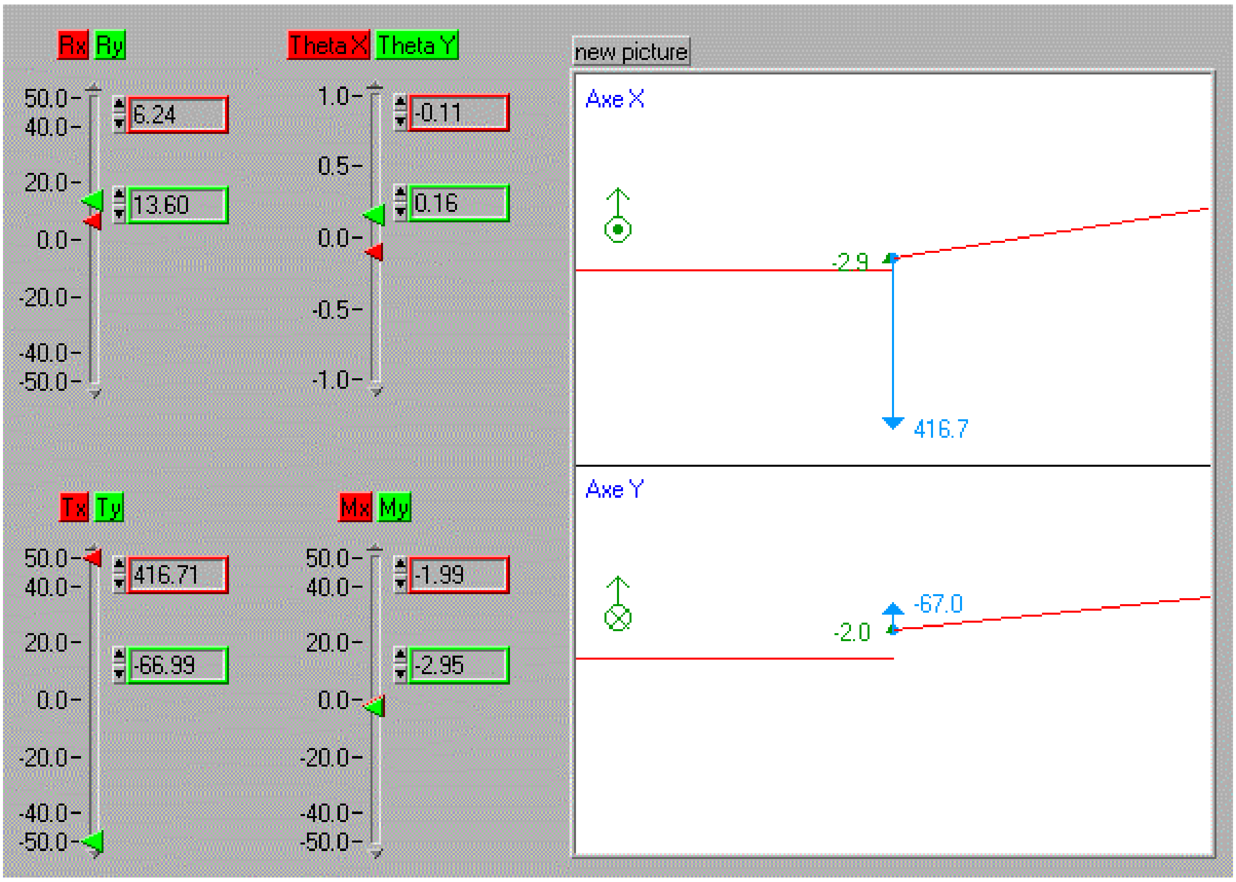
Small torque



Virtual instrument describing the relative positions of the shaft ends (in red Rx and Ry radial misalignemnt and Thetax and y for angular misalignment), the shear coupling reactions in daN (Tx and Ty) and the bending moment reactions (Mx and My) in daNXM.
The torque transmitted is -480 NXM.

The misalignment is almost the same as with zero torque.

Large torque.



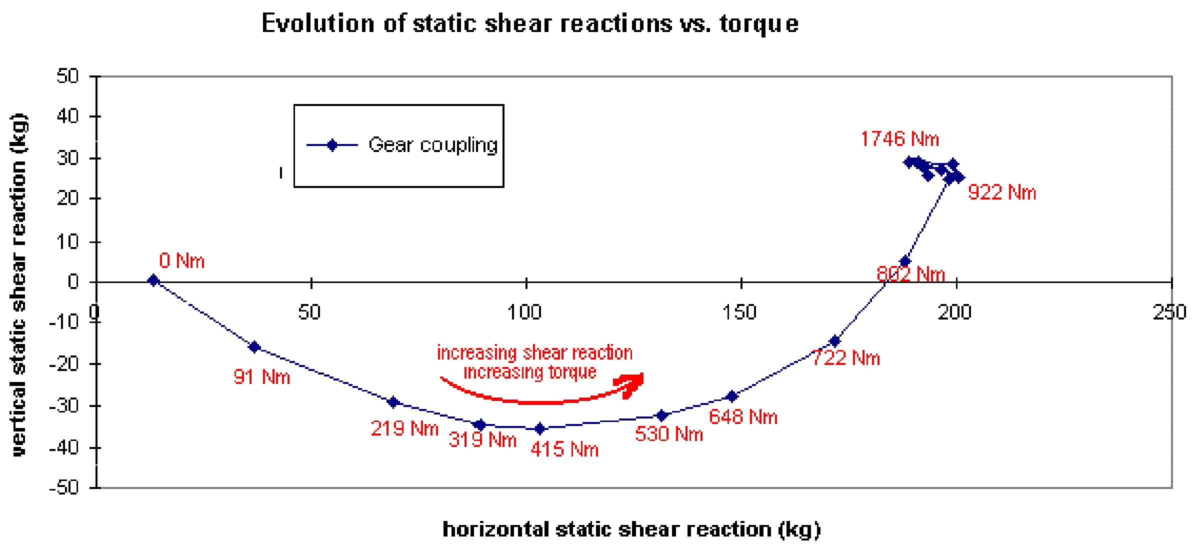
Same as above except that the torque is at the nominal rating of the coupling (1800 NXM) and the reactions are way up whereas the local misalignment of the shaft ends near the coupling approaches zero.

As a result, the coupling behaves like a rigid one. The shaft bends (only tips of the shaft ends are shown in the above vi.

Gear coupling reactions and gear coupling misalignments vs. torque.

The following diagrams were obtained on the test rig for gear couplings. Others follow for disc couplings and couplings with elastomer blocks.

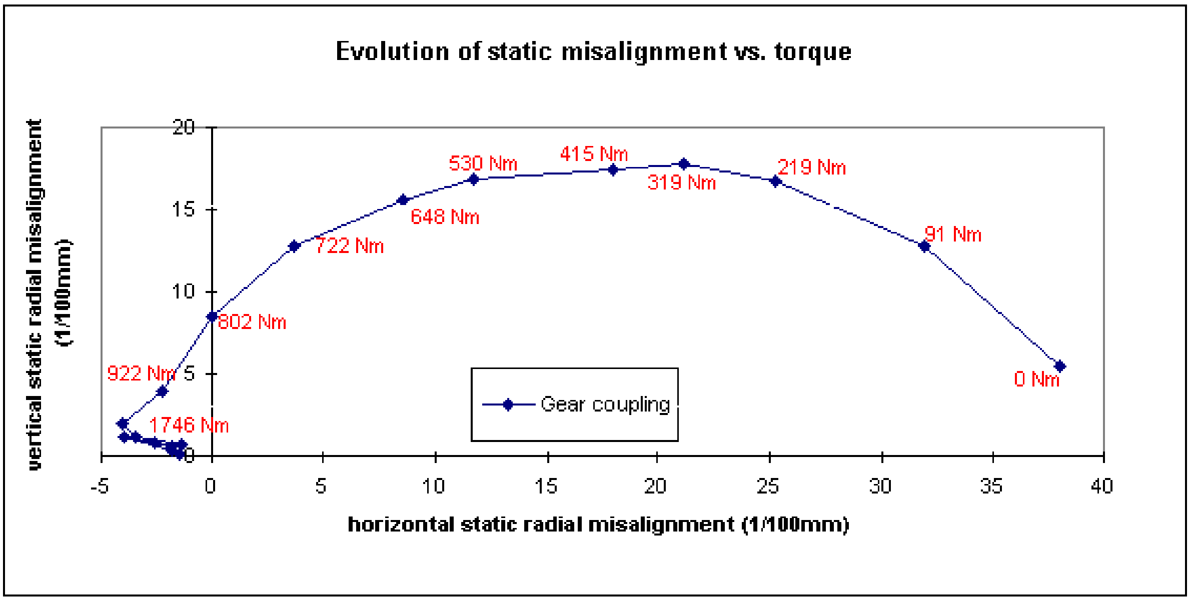
Reactions vs. torques



Increasing the torque causes the gear coupling radial reaction to rise substantially up to 2000 N for an initial 38/100 mm radial misalignment. This trend holds on up to 900 NXM. From there on, the reactions level off because the local coupling misalignment is almost zero (cf. below). At high values of torques, the gear coupling behaves like a rigid one bending the shaft ends and loading bearings.

One notices that the coupling reaction exhibits a component perpendicular to the original misalignment. This is due to friction. The component increases with torque, then levels off at ca 415 NXM and finally stabilizes at 250 N when the coupling gets self-aligned (see below

Coupling misalignment vs. torque



The initial misalignment at zero torque is 37/100 mm radial horizontal. The final coupling local misalignment hovers around -3/100 mm at high values of torque. Since bearings do not move, this means that overhung shaft ends bend. In between, some radial vertical misalignment builds up. It is due to the friction forces developing between the coupling teeth. A good model for gear coupling can be found in "Couplings and Shaft Alignment" by M. Neale, P. Needham and R. Horrell , Mechanical Engineering Publication, London. Based on this model, an average friction coefficient between (crowned) tooth profiles is around 0.12. This can be obtained by examining the reactions at the crossing point of the clearance curve vs. torque at zero horizontal clearance.

Note that Neales's model tells that angular misalignments cause little gear coupling reaction.

Dynamic (variable) reactions of a gear coupling and vibrations

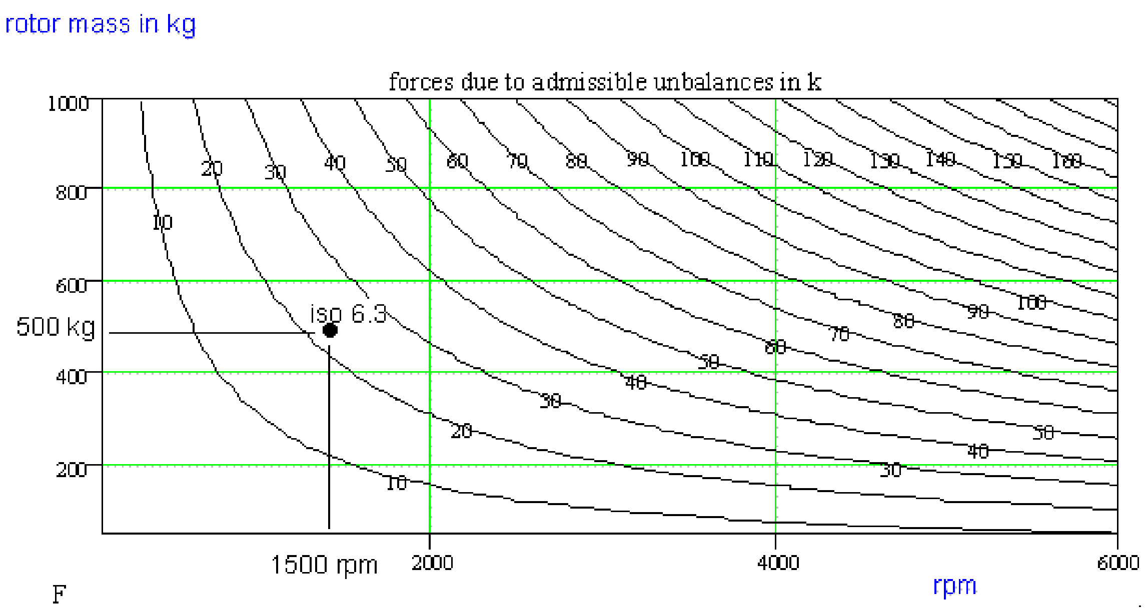
If flexible couplings produce variable reactions, they also produce vibrations. It was interesting to evaluate how bad these can be compared to acceptable unbalances as prescribes by ISO norm 1941B for rigid rotors. Flexible couplings are usually associated with such rotors and often with roller-element bearings. So we tried to figure out what would happen when an induction motor delivers a torque through the same coupling as in the rig.

Let the rotor of a 250 KW 1500 rpm induction motor delivers its torque through the gear coupling. The torque is 1600 NXM. Such rotors have rotors weighing 5000N.approximately weighs 5000 N. It typically loads its two bearings evenly, i.e. 2500N.

With an initial 37/10mm radial vertical misalignment, the radial reaction of the coupling reaches 2000N and loads the nearest bearing even more. As a result the bearing may be totally unloaded. The coupling reaction literally lifts the rotor in its bearings.. For larger initial misalignments it gets worse. This is reported in numerous textbooks. Bearing loads usually affect vibrations, especially when these are thick-film sleeve bearings.

What has is lesser known is how the coupling reactions affect vibrations.

Excitation from residual unbalances according to ISO 1941B vs. gear coupling variable reactions



The above chart was generated from ISO1941B grade 6.3 balancing norm for rigid rotors. How to interpret this? It plots the rotor weights vs. the maximum operational speed. Level lines are labeled in centrifugal forces derived from the ISO admissible unbalances (in daN).

Select 500 Kg for the mass of the induction motor and 1500 rpm as max speed. The admissible centrifugal force is 230 N and splits on both bearings. In most reasonable

machine construction, this will never cause excessive vibrations which will remain well within ISO2372 vibration norms. Vibrations caused by that unbalance will be at 25 Hz.

Now compare the forces with the levels reached with the test rig for the dynamic reactions of a misaligned gear coupling. At twice the rotating frequency, one obtained up to 350 N. This force loads the neighboring bearing even more.

The score is:

- ***Coupling reaction: More then 350 N on the bearing closest the coupling at 50 Hz***
- ***Residual unbalance: 115 N on the same bearing at 25 Hz***

Winner: the coupling reactions! They may cause real vibration problems. This was never reported elsewhere.

Gear Coupling Piloting and unbalances

The following remarks come from Mancuso [] and could not reproduced on a slow-speed rig.

Piloting is defined as the method used to ensure that two connected components rotate around the same axis. The simplest example is mounting a disk with a hole in the center on a shaft. The interface between the hole (bore) and the shaft is the pilot of the assembly. If the bore is not concentric with the disk's outside diameter, then the disk will not rotate around its axis of gravity (center of gravity, or CG), and an unbalance is created. Therefore, a *good pilot* ensures that the two connected components rotate around a centerline which is at the same time the axis of gravity.

For machinery users it seems obvious that rotors must be balanced after disassembly and subsequent re-assembly, particularly because rotors are seldom disassembled, and when they are, the labor involved represents a major expense. The same machinery users, on the other hand, expect flexible couplings to remain in balance even after they are removed from machines, and then reinstalled. This is why piloting of coupling components requires special attention, especially with gear and grid couplings.

Gear couplings have a "floating assembly" which can move axially over the components which are attached to the shafts: the "spacer" or 'hub". This floating assembly must be free to move axially, but at the same time should have no radial play over the shaft-mounted components.

Loose supports are a particular case that applies to gear-type couplings. The figure below shows the piloting area between the hub and its sleeve. A clearance always exists at this pilot because:

- ***The heat transferred to the hub from the shaft, particularly in turbine applications, causes the hub to expand more than the sleeves (which benefit from outside cooling). Manufacturers provide a clearance at the pilot, to avoid the locking of the coupling, as caused by the difference in thermal expansion.***
- ***Centrifugal acceleration has an effect on sleeves than on hubs, particularly because hubs are pressed on their shafts, and the two as a unitized body. Because of larger***

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growth of the sleeve diameter, the clearance in the pilot area increases as a function of speed.

- ***The wear at the hub tooth tip creates a clearance at the pilot.***

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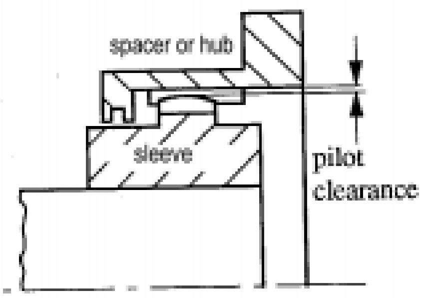

Gear-type couplings will normally have a clearance at the hub-to-sleeve pilot.

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Even with a clearance at the hub to sleeve pilot, gear couplings still operate smoothly at high speeds because of the piloting effect created by torque being transmitted through the involute profile. However, the involute profile pilots the sleeve to the hub only if torque is transmitted from the moment the coupling starts to rotate (which is usually the case). If torque is applied *after* operating speed is achieved, gear couplings can cause severe vibration in the system. Formulae can be used to determine the torque required for the involute profile to re-center the coupling. Gear couplings should not be used in applications where machines operate without torque.

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Gear couplings and lubrication.

Gear coupling must be properly lubricated. One must avoid sludge formation. When lubricated with grease at high rotational frequencies, the lubricant trapped in the grease substrate may be centrifuged to the spacer rim and no longer lubricates gear profiles.

For a proper lubrication, gear couplings welcome some misalignment to ensure some relative motion between gear profiles and, therefore, some renewal of the oil film. The following pictures tell the whole story and was highly appreciated in March 98 by the management of Burgo (a SCOPE client) when explaining why a gear coupling had exploded in their plant.

Why do gear coupling need some misalignment for a proper lubrication?

Lubrication Conditions

The lubrication conditions of a coupling vary from application to application. The correct lubricant for a particular application can be selected only if the particular conditions of that application are understood.

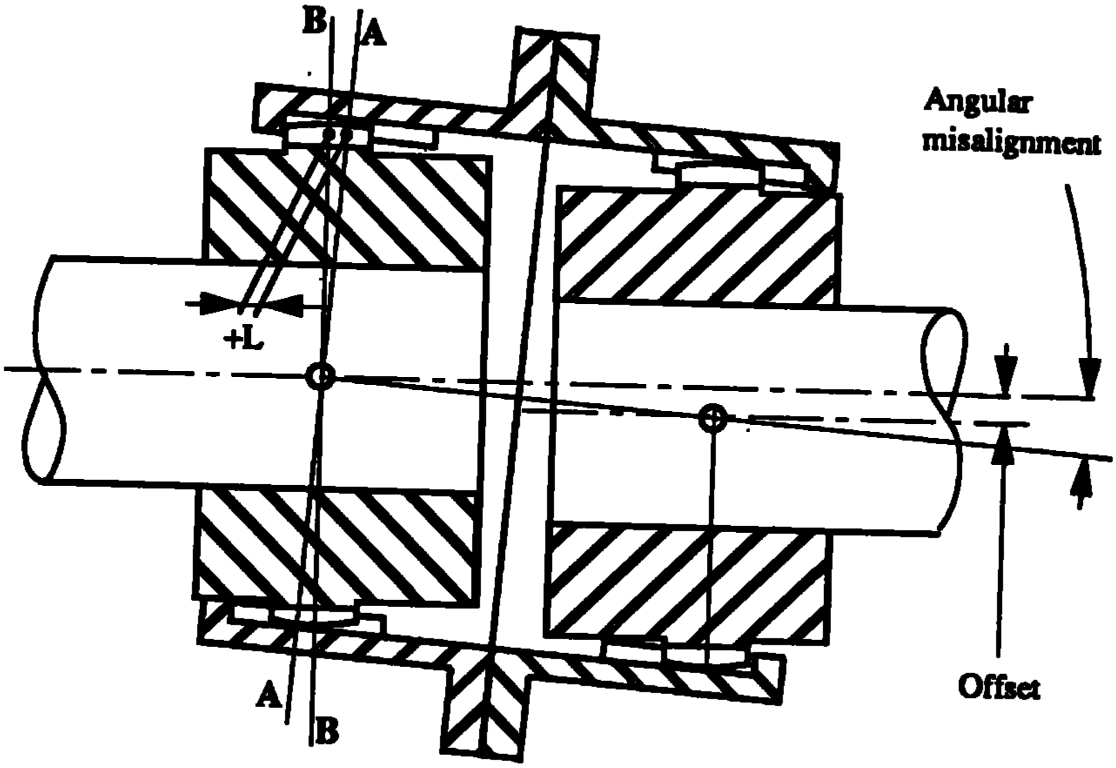
Lubrication conditions are influenced by:

- **Motions inside a coupling**
- **Operating misalignment**
- **Rotating speed**
- **Viscosity of the lubricant**

Note: Gear type couplings were used in the following discussion, as gear couplings are typical of other lubricated couplings.

Motions inside a coupling

Couplings that accommodate misalignment through sliding need lubrication to prevent the wear of the sliding surfaces. The lubrication conditions in couplings are unique and need clarifications. The following figure illustrates how a misaligned gear coupling operates.



The motions inside a gear-type coupling require lubrication; without these motions couplings will not be lubricated even when full of grease or oil.

The hub teeth are placed in the plane B-B, which is at an angle to the sleeve teeth, plane A-A. This angle is the angle of misalignment. Because of the angle between the two planes, the hub tooth shown is displaced to the left by a distance +L. After half a revolution the same hub tooth moves to the right of the plane B-B by the same distance, which is now -L. Hence, each hub tooth slides the distance 2L in half a revolution and returns to the original position after one revolution is completed. The motion of a hub tooth is oscillatory; the oscillation's frequency is equal to the operating speed, and the amplitude is 2L. In addition to the sliding motion described, hub teeth also have a rocking motion.

Influence of misalignment

Lubricant can penetrate between teeth as it follows the oscillatory motion, and in particular during the time the hub teeth are tilted in respect to the sleeve teeth. **Therefore, in order to be lubricated *the coupling should be somewhat misaligned.*** The need for lubrication increases as the misalignment becomes larger; fortunately, as the misalignment increases so does the amount that the hub teeth are lifted off the sleeve teeth. Hence, lubrication conditions improve as the misalignment becomes larger.

From Neale et al

For gear couplings, the coupling alignment capability limits are as explained in Section 3.2.2.

The allowable angular displacement is inversely proportional to speed, and is limited by tooth wear; axial displacement is limited by the length of the teeth. A typical minimum axial displacement is 6 mm, as required in API Standard 67 1, although coupling axial capability need never be a constraint when using gear couplings. In contrast to diaphragm and membrane couplings, the ability of gear couplings to cope with angular displacement is quite independent of their ability to cope with axial displacement. The necessary minimum angular displacement of 0.00075 radians, to maintain adequate lubrication, seems worth reiterating here. There may be variations on the same theme depending on gear profile crowning and the lubricant and the rotational speed.

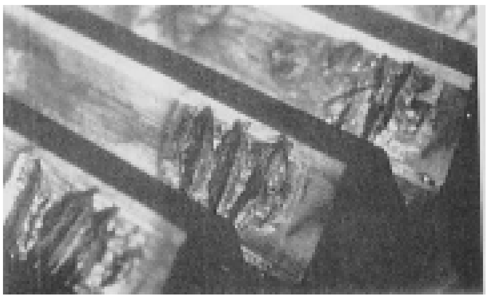
Influence of speed

Another factor that improves the lubrication conditions is the centrifugal acceleration. The time that the hub tooth is lifted off the sleeve tooth, i.e.,. the time available for the lubricant to penetrate between the teeth *becomes shorter*. as the speed increases. On the other hand, the centrifugal acceleration increases with the square of the speed, hence the force that pushes the lubricant between the teeth increases rapidly with speed. The lubrication conditions, as related to wear, improve as the speed increases; this fact was demonstrated by actual tests.

Couplings that operate at very low speeds subject their lubricant to low centrifugal acceleration, therefore have poor lubrication conditions. If a rather consistent grease would be used at low speeds, couplings would wear-out rapidly. Actual tests have shown that lubrication conditions become very poor whenever the centrifugal acceleration is lower than 10 Gs. To compensate for low centrifugal acceleration, slow-turning couplings must be lubricated with progressively thinner lubricants.

In the test performed in the ULB, some poor lubrication causes an important reaction of the coupling perpendicular to the original misalignment according to a model from Neale. This component would decrease at higher speeds. It turned out that after using improved EHP lubricant this cross-reaction remained high. For financial reasons it was not possible to test couplings at nominal torque ratings and higher speeds. It could be partly possible now since the recent revamping of high-speed rig operating from 0 to 3000 rpm up to 125 KW.

Some misalignment is OK for lubrication. Too much causes other problems.

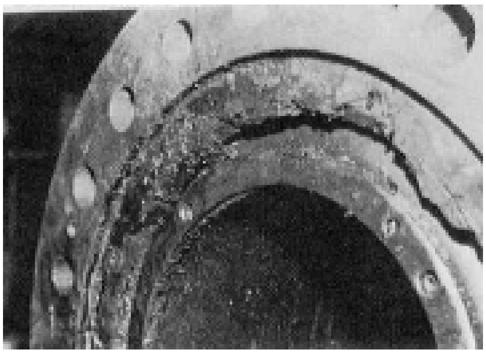


No comment. Respect tolerances for maximum misalignment with the manufacturer. Incidentally they mention relative low admissible values to prevent sloppy alignment jobs.

A case study from Bently Nevada ("Orbit" September 96)

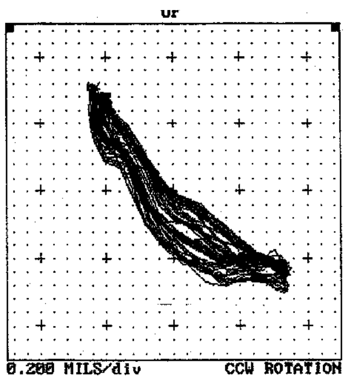
Following a lubrication breakdown due to sludge, a gear coupling ceased to be flexible. The spacer was transmitted the misalignment and endured considerable alternate bending with a peak in load concentration areas like fillets. Vibrations increased as a result with banana-shaped vibration orbits typical of overloaded sleeve bearings. They were lucky to remove the unit from operation and notice what had happened to the coupling. A little later it could explode….

What is sludge?



Prevented by a good oil flow.

What is a banana-shaped orbit?

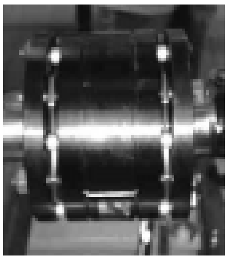


Mainly occurs close to overloaded sleeve (thick-film) bearings. Not applicable directly for roller-element bearings.

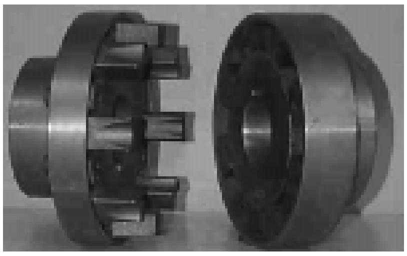
Reactions of other types of flexible couplings

After testing gear couplings from two different manufacturers without noticing any substantial difference of reactions, one moved to two other types of couplings: disc and elastomer.

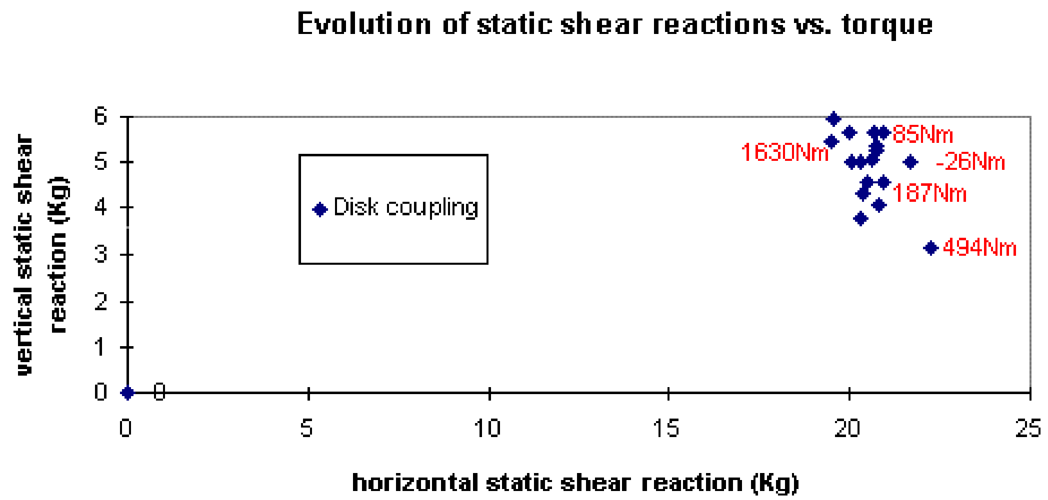
Disc coupling (ESCODISC)

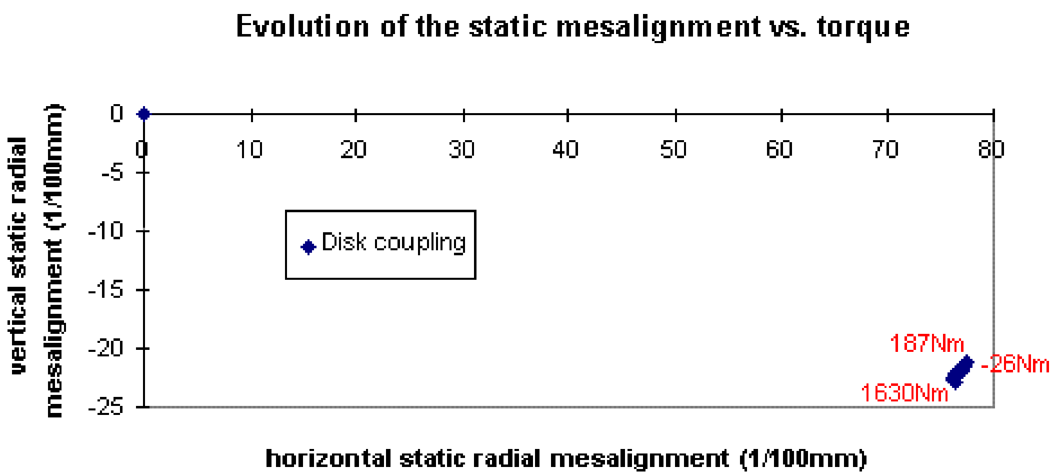


Elastomer

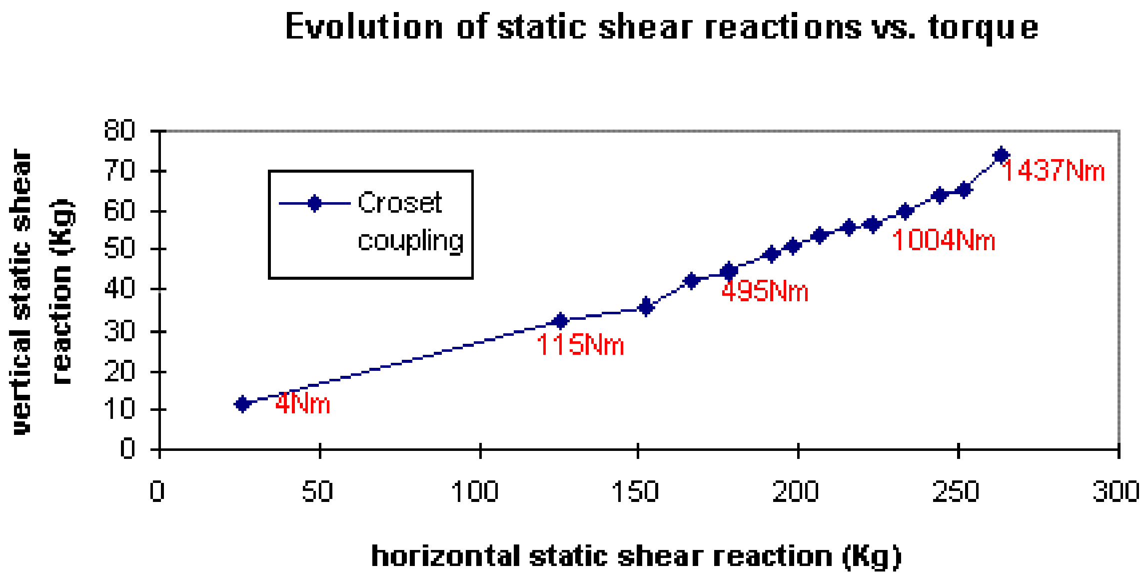


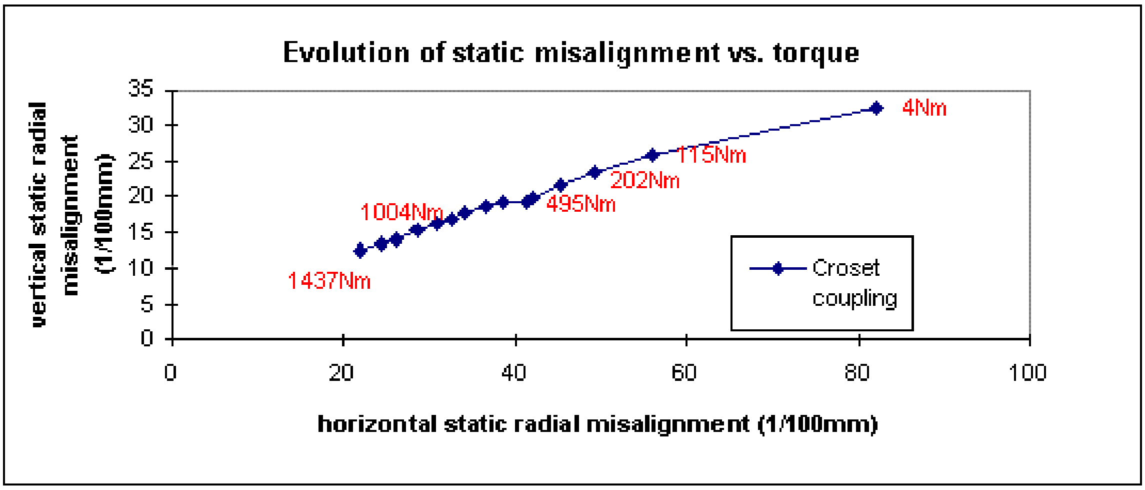
Reactions of disc couplings vs. torque





Reactions of elastomer couplings vs. torque





Comparison with gear couplings

Disk couplings behave extremely well and their reactions are quasi zero for all values of torques. Elastomer couplings exhibit torque-dependent reactions that are nevertheless much less than in gear couplings.

The variable reactions of both couplings that would cause vibrations are always negligible.

General conclusions

In selecting couplings according to their reactions both static (bearing steady load) and dynamic (vibrations), the clear winner is the disc couplings. Other considerations come in when making the final decision. These are summarized hereafter and based on specialized textbooks.

Bear in mind that some so-called "flexible couplings" are not that flexible.

Couplings type	advantages	Drawbacks
Gear	Compact, long experience. Gear profiles wear progressively. Very good to accommodate end motion (axial misalignment) Easy to mount. Some backlash possible	Lubrication and strong torque-dependent reactions Piloting and unbalance. Generates reactions at twice the rotational Poorly operates at very small misalignments and high torque or at zero torque.
Grid	Basically the same as gear.	More flexible in torsion. Strong misalignment may damage cover (grid cuts through the cover). Depending on how one splits the grid (2X1/2 1X1/4, etc.), one can excite vibrations at harmonics of the rotation speed.
Disk	No lubrication. Very little static and dynamic reactions when misaligned. Easy to visualize misalignment through disk flexure pattern. Very rigid in torsion. No piloting and subsequent unbalance. The winner for vibration behavior.	May suddenly break. More sensitive to axial misalignment (end motion) Axially flexible (axial vibration modes). Not investigated in research. Rather bulky.
Elastomer	Compromise between dry and lubricated couplings in term of reaction and end motion. Some may be difficult to mount, e.g. when inserting elastomer blocks one must move hubs axially.	Beware internal heating due to hysteretic losses and chemical agents and aging. Not recommended for large ratings. Etc.

Conclusions

Tests on gear couplings indicate that the flexibility of some so-called flexible couplings is a myth. When misaligned and transmitting torques close to their maximum rating, such couplings may alter the bearing loads considerably and raise vibration levels higher than those caused by admissible residual unbalances according to balancing norms. In other words, when misalignment looms, balancing may never succeed to bring vibration levels to admissible levels.

Examining vibrations with the most advanced techniques is unlikely to indicate in which direction a flexible coupling is misaligned. Variable reactions from couplings rotate without exhibiting any preferential component that could be linked with the direction of misalignment.

This study confirms for the case of shaft lines with flexible couplings what many practitioners and vibration specialists have long claimed about the incidence of misalignments on vibrations: more than 50 % of unexplained vibrations in rotating machinery originate from misalignments.

It does it with hard figures based on loads and not displacements and vibrations that depend on the frequency response of the structure at hand. It establishes a methodology to evaluate coupling reactions and characterize them. The approach relies on somewhat advanced data processing techniques.

Applying these techniques to disk and elastomeric couplings, one establishes that disk (and probably diaphragm) couplings exhibit the least reactions (both dynamic and static) in presence of torque and radial and/or angular misalignments. Based on these facts, one recommend using them when feasible. Read the next section from Calistrat to get a more balanced conclusion based on other considerations.

Retrofitting lubricated (e.g. gear) with dry couplings (Calistrat + *comments*)

Many coupling users have replaced their lubricated couplings with "dry" couplings; many others are planning to do it. *That is the case in EDF for many types of auxiliary equipmen (according to* Randiranarivo).

When retrofitting with dry couplings, a few items must be clarified:

The main reason users consider replacing lubricated couplings with dry is the ability of dry couplings to operate long periods of time without maintenance (lubrication, or cleaning the couplings of sludge accumulation).

A bad lubrication of gear couplings may lead to catastrophic failures (Burgo incident in Belgium, and "Orbit" September 96 from Bently Nevada)

At the time that dry couplings started replacing gear couplings in special purpose applications, a few engineers believed that the service life of dry couplings was indefinite, at least as long as the alignment stays within acceptable limits. Now that dry couplings have a "long " history, this belief has proved to be only partially true. Concurrently with the

availability of new type dry couplings, the frequency of gear coupling problems started to decrease. What apparently happened is users learned that if they are as careful installing gear couplings as they *must* be when installing dry couplings, many of the notorious gear coupling problems tend to dwindle away.

Perhaps the most important thing that was learned from failures of dry couplings is that, most of the time, they occur without any warning, and they have, in a few cases, caused severe damages to the connected machines.

That is the reason why coupling manufacturers design disk coupling with a backup inactive gear type coupling for gas turbine shaft lines. The latter acts as an ultimate protection. The disk coupling normally carries the load with the outstanding insensitivity of its reactions to misalignments (consult ESCO transmissions for some advice in Belgium: they are home-grown coupling manufacturers. NDLR Réclame payée en know-how et rien d'autre…remarque à supprimer du document officiel mais introduite en vue d'étouffer toute rumeur).

Lubricated couplings, and particularly gear-type couplings, are significantly superior to all other type of couplings when it comes to power density (amount of torque that can be transmitted per pound or inch of coupling), axial travel ability, and safety in operation *if well lubricated*. In some applications where space is limited, gear couplings can simply not be replaced by other types without great financial outlays.

The above statements are in no way intended to discount the many advantages of dry couplings. Calistrat believes that in considering the many types of couplings available today, a user must be knowledgeable on the subject of couplings, and must use objective reasoning in the selection of the type best suited for a given application.

Refer to Calistrat for a guide to best select the type of couplings, *knowing that many advances have occurred in the design of dry couplings like disk*.

For the vibration specialist, disk coupling is a master choice for quiet operation, as compared to gear couplings for the following reasons:

- **They do not cause unbalances due to piloting and variable torque.**
- **They do not generate variable reactions at twice the rotating frequency that depend on torque.**
- **They do not load the neighboring bearings when misaligned and transmitting high torques. With sleeve bearings disk couplings ensure some vibration stability.**

Disk couplings have advantages for maintenance:

- **Disk couplings need no lubrication.**
- **They need not be misaligned to operate properly at high torques and they behave well at zero torque.**

But as shown above, other considerations may temper this choice:

- **Gear couplings usually fail more progressively, though their spacer may sometimes explode with very poor lubrication.**

- **They better accommodate end motion due to conflicting thrust bearings.**
- **They are very compact.**

This document was created by G. D'Ans.