COUPLINGS — A USER'S POINT OF VIEW

by

Charles Zirkelback

Senior Staff Engineer

Union Carbide Corporation

Port Lavaca, Texas

Charles Zirkelback is a senior staff engineer with Union Carbide Corporation in the Maintenance Department at their Seadrift plant. He is responsible for rotating machinery reliability. His past experience in the field of machinery has been in plant maintenance, machinery reliability, and troubleshooting assistance to various plants.

Mr. Zirkelback received his B.S.M.E. degree from Mississippi State University and his M.M.E. from the University of Houston. He is a member of ASME.

ABSTRACT

Couplings are one of the critical elements in a turbomachinery system. Malfunctions and failures result in significant outage time that, in most cases, is very costly to the user. This paper will deal with the application of couplings used in turbomachinery in petrochemical plants. A discussion of design selection, installation, operation, maintenance, retrofitting to improved designs, and experiences will be presented.

INTRODUCTION

The flexible coupling in a turbomachinery package represents a small percentage of the cost. However, it accounts for a disproportionately large percentage of outage time and machine problems. It is therefore in the user's best interest to take great care in this critical area where his choices greatly influence the long term reliability of the machinery system. If the important task of coupling selection is left to the machinery manufacturer, it will naturally be a choice that will meet specifications at his lowest cost. This, in many cases, will not produce optimum results from the user's viewpoint. So many options are presented to the user, making it difficult to choose the best for his application. This paper will develop points to consider in making these choices.

The proposed API 671 has done an excellent job of specifying both gear and diaphragm type couplings and should be used as a guideline once the choice of design type has been made.

Coupling installation has taken on new importance with the diaphragm type. Installing one outside its limitations virtually guarantees failure. Poor installation (alignment) will likely not be detected until failure results, whereas in the gear type poor installation is immediately detectable via vibration.

Replacing problematic gear type couplings with the diaphragm type has contributed to better equipment reliability and reduced maintenance costs.

WHY USE A FLEXIBLE COUPLING?

The coupling serves to connect the shaft between the driver and driven equipment in such a manner that it will transmit the required torque without imposing undue stresses on the shafts and bearings due to inherent misalignment and axial displacement. This can, in some cases, be accomplished without using a flexible coupling, i.e., with a solid shaft. However, it is rare to see this simple but superior technique used, particularly where the driver and driven equipment are produced by different manufacturers. Greater care must be taken to insure proper alignment with the solid shaft coupling, or bearing damage and shaft breakage may result. Quill shafts are also a means of obtaining flexibility without the use of flexible couplings. It should first be determined that a flexible coupling is required before using one. It seems that the petrochemical industry has, without due consideration of solid couplings, committed itself to the almost total use of flexible couplings, thus introducing unnecessary complexity.

COUPLING SELECTION

After all the data required for selection has been acquired (such as maximum rated power, maximum rated speed, maximum torque, the geometry that the coupling must fit into, the thermal growths of each machine), the next task is to determine what type coupling is best for the application. Overall choices are a solid shaft, gear type coupling, or a diaphragm type. Until about ten years ago, the gear type coupling was the standard choice. The advent of the diaphragm coupling gave the industry new features and advantages that solve many of the chronic problems that were characteristic of the gear type coupling.

ADVANTAGES OF FLEXIBLE DIAPHRAGM OVER GEAR TYPE COUPLINGS

1. No lubrication required, thus eliminating the need for regreasing or special oil filtration to reduce sludging.
2. Will tolerate greater parallel and angular misalignment without the distress wear that results from large misalignment in a gear type coupling.
3. There are no rubbing or sliding parts to wear. When applied within the fatigue limitations of the materials, the diaphragm type coupling will give much longer life.
4. There are a lot fewer dynamic balance problems since there are no pilot/tooth tip clearances that will allow the spool to crank and create imbalance.
5. There is much less angular moment, which is predictable since it does not depend on an indeterminable coefficient of sliding friction. Seven to ten times less angular moment is produced with a diaphragm coupling.
6. It lasts as well at maximum rated misalignment and axial distortion and load as at zero misalignment. In the gear

type, the wear rate depends on the degree of misalignment, load, speed, and adequacy of lubrication.

7. Zero backlash: Backlash in a gear type coupling can amplify tooth loading from torsional vibrations that may be present.
8. Longer life in radial and thrust bearings due to predictable and lower moment and thrust loads.
9. High and low temperature capability is not limited to the lubricant's temperature limitations.
10. Coupling hub to shaft fit fretting wear is practically eliminated, due to lower angular moment.
11. Hub, sleeve, and spool cracking is common in gear type couplings due to large angular moments produced.

DISADVANTAGES OF FLEXIBLE DIAPHRAGM COUPLINGS

1. Limited axial travel and is less forgiving in shaft separation error. The axial growths of the machines must be known and the rotor accurately located axially to insure success.
2. Axial resonance that if, in the range of the operating speeds or multiples of it, must be dealt with in original design.
3. Failure mode *may* allow runaway without warning; wear in gear teeth is progressive and will normally give warning of an impending runaway.
4. Heat generation due to windage. It does not have the lubricant as in a continuous lubrication gear type coupling to dissipate heat. This can be dealt with in design.
5. The gear coupling will be a smaller diameter if designed on the basis of torque.

DISCUSSION

Instantaneous failure of the diaphragm type coupling, permitting machine runaway, is the greatest risk in this design. However, the gear type coupling is not immune to runaway. Gear type coupling runaway can result from loss of gear teeth due to wear which is gradual and normally gives warning. Fatigue cracking of hubs, sleeves or spools, which the gear type coupling is more likely to experience, can be instantaneous and with little warning.

Eliminating shaft to hub fit fretting by reducing the angular and axial forces transmitted from one machine to the other will avoid the high cost of recutting or replacing the shaft and coupling hub. This also reduces the need for special hub/shaft fastening such as hydraulic mounting. The flexible diaphragm will reduce the transmitted axial forces. Since this axial force is more predictable in a diaphragm coupling, use of smaller energy saving thrust bearings is allowed.

COMPARING AVAILABLE DIAPHRAGM AND DISC COUPLINGS

Considering the above advantages and disadvantages, the requirements of our specific application and a review of the specific data supplied by the coupling manufacturers, the appropriate gear type or diaphragm type coupling can be chosen. There are significantly different designs available in diaphragm and disc type couplings using flexible metal membranes to consider. A choice of the best diaphragm coupling for the application should first be made before comparing to the gear type. There is the single diaphragm type, the single convoluted/wavy profile type, the multiple convoluted diaphragm type, and the bolted flexible disc type. Table 1 and Table 2 show that, unlike gear type couplings which all have similar mechanical characteristics, the diaphragm differs in general mechanical characteristics according to type.

ANALYSIS OF MECHANICAL DATA

In connecting the two machines, the coupling can introduce problems that must be dealt with.

1. The torsional stiffness and WR^2 of the coupling must not produce torsional vibrations; that is, not tune the system to the rotating speed. Computer programs are employed to avoid this problem. On retrofitting, matching the torsional stiffness and WR^2 of the old design is sufficient, if a torsional vibration problem is not present in the existing design.
2. The lateral vibration response of the system should be checked out via computer also. The lateral response will depend on the overhung moment and the WR^2. A judgment can be made on this effect by comparing the critical speeds of the existing design if retrofitting.
3. The axial stiffness will affect thrust bearing loads, particularly if the axial force from the coupling is a significant portion of the axial load.
4. The bending moment is a good measure of how much radial force one machine transmits to another. Radial bearing wear/distress, vibration, hub/shaft fretting, hub and spool flange cracking, and internal seal rubs can all occur due to high bending moment.
5. The axial natural frequency must not be near one times or lower multiples of running speed. High diaphragm stresses and failure can result if a coupling spool resonates.

INSTALLATION

Whether a gear, diaphragm, disc or rigid type coupling, it must be installed such that it does not operate outside of its alignment capabilities. To insure this, the thermal and mechanical movement of each machine with relation to each other must be known so that cold condition alignment can be established. The equipment manufacturer's estimated rise and axial displacement data are first used. On critical installations and problematic machines, it is justified to monitor the movements in the field. It is not uncommon to see actual movements vary 50% from predictions.

It is found that optical alignment equipment, for determining hot rise, and a computer for the shim change calculations work well. The commercially available programmable calculators reduce errors and are real time savers, when compared to plotting (graphing) the alignment data.

The coupling manufacturer should be consulted if there is any doubt or question on the alignment procedure or tolerances for the particular coupling being installed.

For the continuous lubricated gear type, the oil spray must be of adequate volume (correct opening size) and directed to the appropriate point. Observing the oil spray pattern with the cover open or with a borescope is necessary to insure proper lubrication.

EXPERIENCES

A compressor, originally using four gear type couplings on two trains, at 12,500 rpm, had coupling gear teeth wear, severe coupling hub and shaft fit fretting, hub breakage, and resulting

TABLE 1. COMPARING FLEXIBLE DIAPHRAGM/DISC COUPLINGS

CHARACTERISTIC	SINGLE DIAPHRAGM (SD)	SINGLE DIAPHRAGM WAVY PROFILE (SDWP)	MULTIPLE CONVOLUTED DIAPHRAGM (MCD)	BOLTED DISC (D)
Axial Spring Rate	Nonlinear	Linear	Linear	Nonlinear
Axial Stiffness	Stiff/Moderate	Moderate	Soft	Soft
Axial Displacement	Requires 2 diaphragms per end to obtain large displacements	Same as SD	Large	Small
Angular Misalignment	⅓°/diaphragm 4 diaphragm maximum	⅓°/Diaphragm	½°/diaphragm pack 2 diaphragm pack maximum	⅓°/disc pack 2 disc pack maximum
Runaway Potential	Immediate with little warning; may need redundant gear drive for special application.	Same as SD	Outer diaphragms fail in bending and produce imbalance before failing torsionally	Will give warning
Overhung Moment	Low with single diaphragm normally lower than gear type	Same as SD	Moderate	Moderate to high
Diameter	Large	Large	About 2″ less than types SD & SDWP	About same as MCD
Axial Damping	None	None	Air damping between separated diaphragms. Available with special air damper.	Friction damping from rubbing discs
Failure Mode	Fatigue of diaphragm in bending mode, if operated outside alignment limitations.	Same as SD	Fatigue of outer diaphragm in bending mode, self-healing, less bending stress on remaining diaphragms.	Fatigue, can be initiated by fretting and bolt hole stress concentrations. If fails, may destroy adjacent equipment with large asymmetrically radial and axial forces produced by bolt engagement.
Diaphragm Materials	Coated high strength steel	Same as SD	Variety of noncorrosive materials available	Same as MCD
Replaceable Diaphragm Element	No	Yes	Yes	Yes
Inspection Interval	Same as type SDWP & MCD	Same as SD and MCD	Same as SD and SDWP	Shorter due to disc fretting.
Safety from Flying Parts	Good	Good	Good	Most models do not restrain spool during disc failure. Disc parts can fly from element pack.
Pilot Fit Elements	Available/standard	Available	Standard	No
Lateral Stiffness	Stiff	Moderate	Soft	Stiff

TABLE 2. MECHANICAL DATA COMPARISON OF A GEAR, MULTIPLE CONVOLUTED DIAPHRAGM & SINGLE DIAPHRAGM TYPE COUPLING

TYPE	GEAR	MCD	SD
Required Horsepower (Hp @ rpm)	25,000 hp @ 5,100	Same	Same
Required Torque (in-lb)	308,824	Same	Same
Rated Torque Diameter (in-lb)	345,200 11¾″	308,824 14″	316,000 16.250″
Misalignment Capacity			
(± Degrees/Diaphragm)	±.044*	±¼°	±⅓°
Parallel Offset (in)	.084	.248	.322
Required Axial Capacity (in)	.500	.500	.500
Axial Capacity (in)	.750	.625″	.570
No. of Diaphragms	2 gear elements	2	3
WR^2 (lb-in^2)	4,160	6,750	3,739
Torsional Stiffness (in-lb/Rad)	28.7×10^6	13.13×10^6	7.5×10^6
Total Weight (lb)	370	317	256.3
Axial Stiffness (lb/in)	NA	6,600	6,842
Maximum Axial Force (lb)	4,632*	2,062	1,950
Bending Moment @ Maximum Misalignment (in-lb)	29,490*	1,787	2,600
Overhung Moment (in-lb)	3,335	3,641	2,597
Axial Natural Frequency (cpm)	NA	2,500	2,606/3,682

*NOTE: 1. The bolted disc type coupling was not considered because it would not meet the required axial displacement.
2. The maximum axial force and bending moment for the gear type coupling is based on .15 coefficient of friction.
3. Misalignment capacity of gear type coupling based on maximum tooth sliding velocity of 1.3 IPS.
4. The single diaphragm (SD) required two (2) diaphragm elements on one end to meet the required axial displacement. This introduces a greater degree of complexity.

high vibration. Coupling life was one to two years. Oil sludging was present, and the coupling oil dams were cut out to provide oil flushing. This helped, but sludging persisted. A ½ micron coupling lube oil filter system was installed and sludging was significantly reduced. Concurrently, the machines were optically aligned and the coupling teeth were nitrided, but the problem was only alleviated, not eliminated. Diaphragm couplings were installed and have been running for two trouble-free years. There has been an overall improvement in vibration levels, and inspection has shown a total absence of shaft fretting. Several retrofits from gear to diaphragm couplings have yielded similar results.

A propane compressor driven by a condensing steam turbine, 9,000 H.P. at 6,000 rpm, experienced high vibration on the shaft monitoring system. An orderly shutdown was in progress when the gear coupling failed, throwing its spool into and rupturing a propane line. A fire ensued. The compressor bearing housing was damaged and the turbine shaft was bent ⅝″. This failure points out that gear type couplings do give warning of impending failure, but the warning may be of short duration.

A horizontal water pump and motor was extensively damaged when the disc-pack on the motor side failed. The coupling spool moved off center and the unbalanced weight broke the bearing housing from the pump and bent the pump shaft. The motor shaft was driven against the outside end bell damaging the motor.

There is no means to restrain the spool once a disc-pack fails in this design. Failure has been catastrophic in several instances. The hazard to property and persons from catastrophic coupling failure must be avoided.

SUMMARY

1. The effort spent in design selection and application will be rewarded with increased reliability and plant safety.
2. The coupling must fit the dynamic and geometry characteristics of the machinery.
3. The flexible diaphragm couplings are proving to eliminate many of the problems of the gear type coupling.
4. Retrofitting from problematic gear to diaphragm couplings is a profitable business.
5. Proper installation of diaphragm type couplings is required to prevent failure, since it will not warn of poor installation via vibration such as the gear coupling does.

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