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Retrofitting Gear Couplings with Diaphragm Couplings

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Retrofitting Gear Couplings with Diaphragm Couplings

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Here are guidelines for selecting couplings and modifications that can be made to accommodate system performance. An actual syngas train retrofit illustrates the principles

Abstract

Retrofitting a coupling should not be an afterthought when upgrading a system. Couplings are an integral part of a drive train and should be a major consideration. This article will discuss guidelines that should be used when replacing gear couplings with diaphragm couplings.

Reviewed will be the coupling selection process: how and to what extent the desired diaphragm couplings should be matched to the gear coupling. Also discussed will be the details of coupling modification that can be made to accommodate system performance. Included will be how changes in materials, configuration and design can help tune a diaphragm coupling to meet the characteristics of the previous gear couplings.

The article also will discuss the retrofit process for a specific syngas train at International Minerals and Chemical Corp., Sterlington, La.

Introduction

Diaphragm couplings have been widely used in petrochemical applications for 10 to 15 years. Many of these applications have run continually for three to five years without unscheduled shutdowns due to coupling problems. Therefore, this has caused a trend towards using diaphragm couplings. Fig. 1 shows diaphragm coupling sales versus gear coupling sales by one coupling manufacturer. However, replacing a gear coupling with a diaphragm coupling is not always easy. Most systems have been tuned with the coupling (lateral and torsional) and to install a diaphragm coupling into a system without matching the existing coupling characteristics can prove unsuccessful. Along with matching the coupling characteristics, diaphragm couplings are inherently larger than gear couplings and therefore replacement normally will have interference problems with the equipment and/or the coupling guard.

Some of the coupling characteristics that must be considered are:

- Weight
- Center of gravity (CG)
- Torsional stiffness
- Balance requirements
- Size envelope required.

Later we will discuss the coupling selection process and how and to what extent the desired diaphragm coupling should be matched to the gear coupling. Also, other things must be considered, such as a diaphragm coupling's axial natural frequency (ANF) and the temperature rise in the coupling guard.

The alternative to matching existing coupling characteristics is to

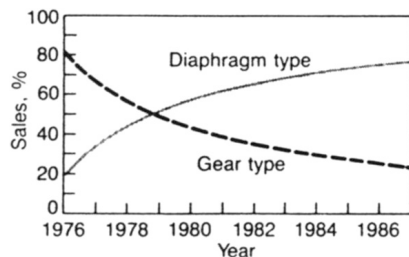


Fig. 1: Percent of sales, high-performance diaphragm couplings vs. gear coupling.

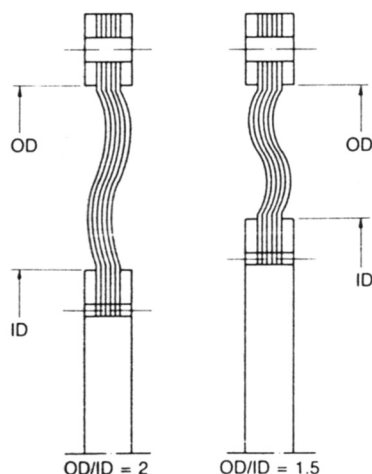


Fig. 2: OD/ID ratio comparison for a diaphragm coupling.

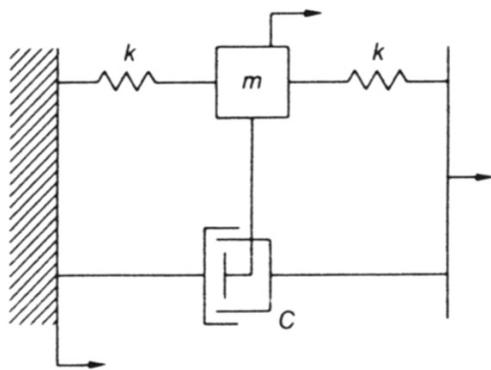


Fig. 3: Free body of diaphragm spring mass system.

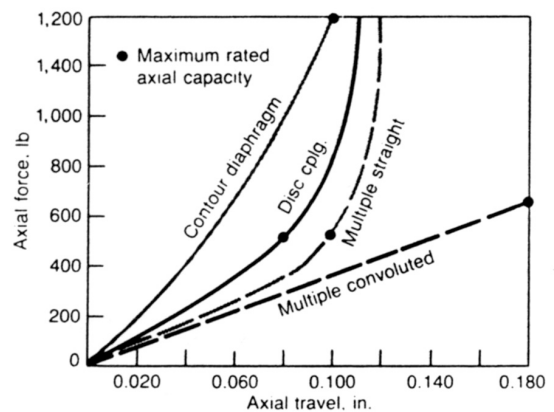


Fig. 4: Axial stiffness of metallic membrane couplings.

perform a complete lateral and torsional analysis on the entire system, which can be expensive and time consuming.

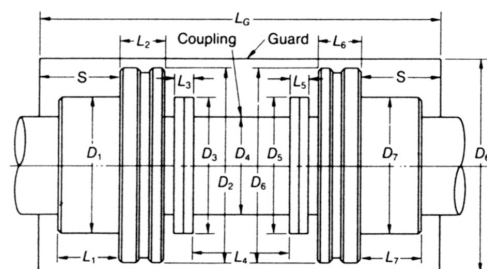
General Guidelines for Retrofitting Couplings

To properly retrofit a coupling for an existing application the following basic information should be supplied to the coupling manufacturer:

1. Shaft or bore sizes, amount of taper, keyway dimensions and hub length.
2. Horsepower and/or torque to be transmitted. Specify continuous (steady-state) and peak (transient) conditions.
3. Speeds: minimum, normal, maximum and any dwell speeds.
4. Distance between shaft ends and required axial movement and misalignments.
5. Unusual operation conditions: ambient temperature, type of atmosphere present (hydrogen sulfide, chlorine, etc.).

In addition to the above, the following information is very important on retrofit applications:

- A drawing of the coupling being replaced showing: weight and WR^2 , CGs and torsional stiffness.
- Drawing of existing coupling guard.
- Drawing or schematic showing system configuration



and equipment involved.

- History of present coupling (how long in service, problems experienced, etc.).

The following guidelines usually result in success:

1. If the operating speed is 3,600 rpm or less, the weight of the new coupling should not be greater than 20% above the existing coupling. Torsional stiffness should be within $\pm 25\%$ of the existing coupling.
2. If operating speed is over 3,600 rpm and equal to or under 6,000 rpm, the weight of the new coupling should not be greater than 15% above the existing coupling. The torsional stiffness should be within $\pm 20\%$ of the existing coupling.
3. If operating speed is over 6,000 rpm, the weight of the new coupling should not be greater than 10% above the existing coupling and the torsional stiffness should be within $\pm 15\%$ of the existing coupling.

If the equipment has been prone to vibration problems, or one or more of the above guidelines are not obtainable, then a new system analysis should be performed for the system.

To ensure complete operating success, the following also should be reviewed:

- ANF analysis—Calculations for the couplings ANF should be done to assure that calculated ANF is not within $\pm 20\%$ (Actual $\pm 10\%$) of any operating speed or range. In geared trains, consideration also should be given to forcing frequencies other than the couplings own rotational frequency.
- Coupling guard temperature—Calculations should be performed using drawings of the equipment housing and the existing coupling guard to assure that the operating temperature in the coupling guard is within safe limits. As a rule of thumb, if more than 2 in. clearance exists between the coupling OD and guard, detailed calculations are not required. If the analysis shows a problem, then modifications to the equipment housing, coupling guard and/or coupling itself may be required.

Design Parameters That Affect Coupling Sizing and Selection

Material and coupling design. Most couplings are selected from a catalog based on bore size and/or

torque capacity. However, in the case of retrofits, some modifications to these couplings may be required.

The most significant change in a coupling's capacity (torque and bore) can be made by changing the material of the coupling components.

Hub and spacer material. Typically, most high performance coupling components are made of 4100 series steels. Most commonly used is 4140 heat treated material to produce the following properties: ultimate strength: 135,000 psi, yield strength: 105,000 psi.

Hubs can be manufactured from:

| Material | Hardness, BHN | Ultimate strength, psi | Yield, psi | Strength increase factor |
|----------|---------------|------------------------|------------|--------------------------|
| 4140 | 270 to 300 | 135,000 | 105,000 | 1.0 |
| 4140 | 301 to 330 | 150,000 | 120,000 | 1.15 |
| 4340 | 311 to 335 | 150,000 | 130,000 | 1.25 |
| 4340 | 336 to 360 | 160,000 | 140,000 | 1.3 |
| 15-5 PH | Cond. 1025 | 160,000 | 150,000 | 1.4 |

In applications where cyclic and/or reversing torques are present, improvements in the endurance properties of the part can be made by the following (strength increase factors):

1. Improvements in surface finish (1.1 to 1.2)
2. Improvements in radii and transitions (1.15 to 1.50)
3. Shot peening of the highly stressed areas (1.15 to 1.3)

In a few applications where torsional stiffness of the coupling had to be greatly reduced (30 to 50%), titanium spacers have been used. Titanium alloys such as 6AL-4V have tensile strengths almost equal to some of the steel alloys used, with an ultimate strength of 170,000 psi, and a yield strength of 160,000 psi, while having a shear modulus of approximately half that of steel (steel 11,500,000 psi and titanium 6,000,000 psi).

These improvements in properties not only help with torsional tuning but also can help tune a diaphragm coupling spacer out of an ANF.

Changes in diaphragm material and design.

Diaphragms are usually made of the following materials and have the following relative strengths:

| Material | Endurance strength, psi | Strength factor |
|----------|-------------------------|-----------------|
| 304 HH | 70,000 | 1 |
| 4140 | 70,000 | 1 |
| 4340 | 80,000 | 1.15 |
| 15-5 PH | 90,000 | 1.30 |

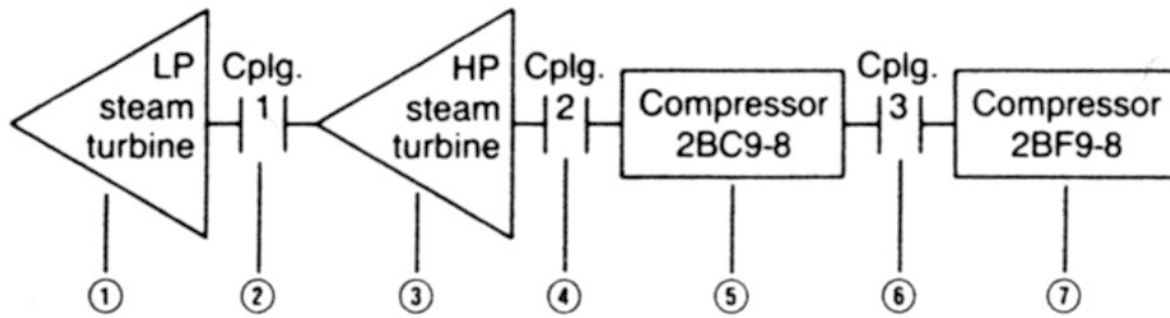


Fig. 7: Syngas train

Various changes in diaphragm construction also can be made. The diaphragm(s) thickness can be changed. An example of this: A 1.25 increase in thickness will increase torque capacity by the same amount, but it will reduce flexibility of the coupling by approximately 50% or proportional to thickness cubed (t^3).

$$t/(1.25 t)^3 \text{ or approximately } 50\% \quad (1)$$

The ratio between the OD and ID of the diaphragm can be changed (Fig. 2). A ratio of 2 (OD/ID) can be reduced to 1.5. This would increase torque capacity by approximately 2.0 and reduce axial flexibility by 33% and angular flexibility by 50%, as shown in the following example:

| Coupling Size | OD/ID | Torque capacity in.-lb | Misalignment | Axial capacity |
|---------------|-------|------------------------|--------------|----------------|
| 8-7 HP | 2 | 56,000 | 1/2 degrees | ± 0.150 in. |
| 8-7 RR | 1.5 | 100,000 | 1/4 degrees | ± 0.100 in. |

Axial natural frequency. Diaphragm couplings exhibit an ANF resulting from having a mass (spacer, adapters, etc.) suspended on springs (diaphragm packs). (Reference: Fig. 3).

$$F_N = 375 \sqrt{K_A/W} \quad (2)$$

K_A = Stiffness of entire coupling, lb/in.
 F_N = The natural frequency in cycles per minute
 W = Weight of center section (lb).

Many metallic membrane couplings have linear axial stiffness or exhibit linear stiffness within certain axial travels. The following couplings exhibit linear stiffness:

1. Multiple convoluted diaphragm couplings
2. Wavy contoured diaphragm couplings
3. Flexible frame couplings
4. Certain disk couplings.

The following couplings exhibit nonlinear stiffness:

1. Tapered contoured couplings
2. Multiple straight diaphragm couplings
3. Most disk couplings.

Fig. 4 shows typical linear and nonlinear stiffnesses of various couplings. For couplings that have a linear stiffness, only one ANF value exists. For nonlinear stiffness many ANF values may exist.

Heat generation and windage loss. The rotation of a coupling within a stationary guard may result in a temperature increase in the guard due to frictional resistance within the enclosure. The analysis represents the coupling as a disk at its maximum diameter and length (Fig. 5).

There are two main types of horsepower losses:

Disk windage loss—The disk windage power accounts for frictional losses in both ends of the guard. The correlation with rpm and diameter is:

$$hp \text{ loss}_{\text{disk}} \approx rpm^3 (\text{diameter}^5) \quad (3)$$

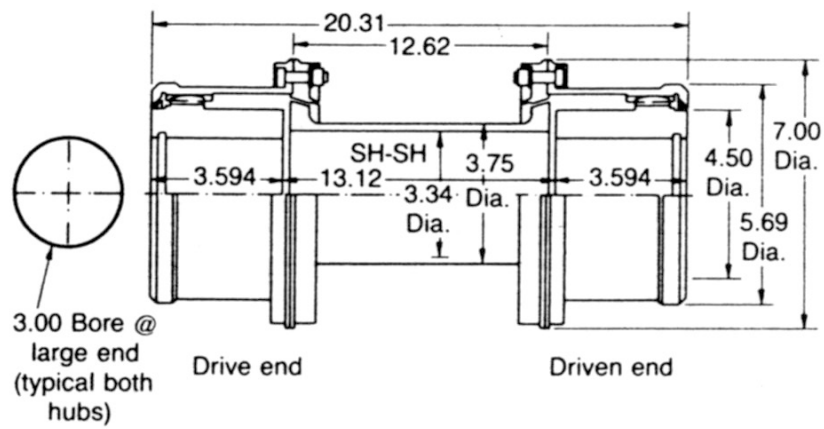


Fig. 8: Original gear coupling in position 2

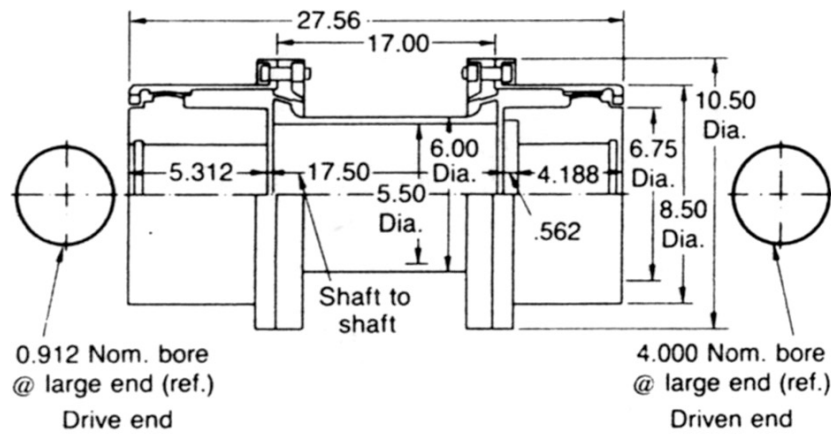


Fig. 9: Original gear coupling in position 4

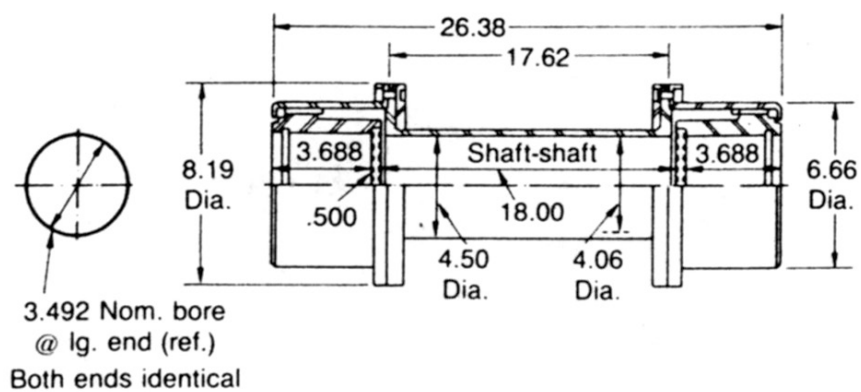


Fig. 10: Original gear coupling in position 6

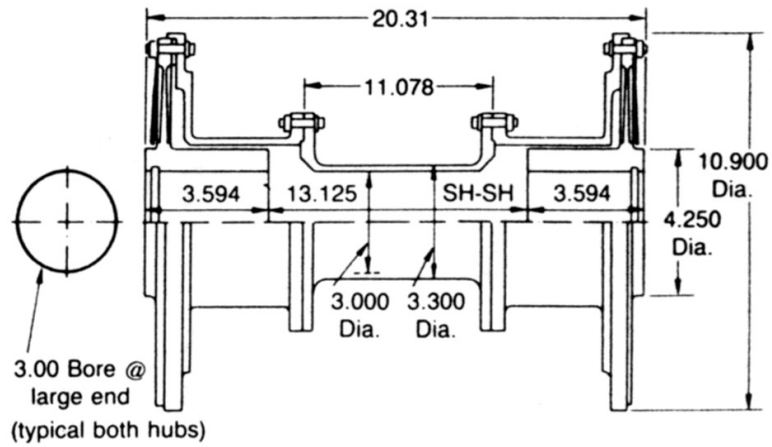


Fig. 11: Position 2 retrofitted diaphragm coupling

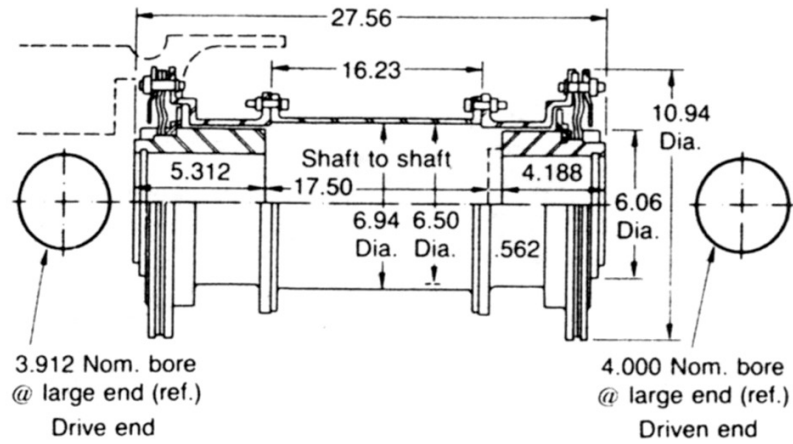


Fig. 12: Position 4 first proposal coupling

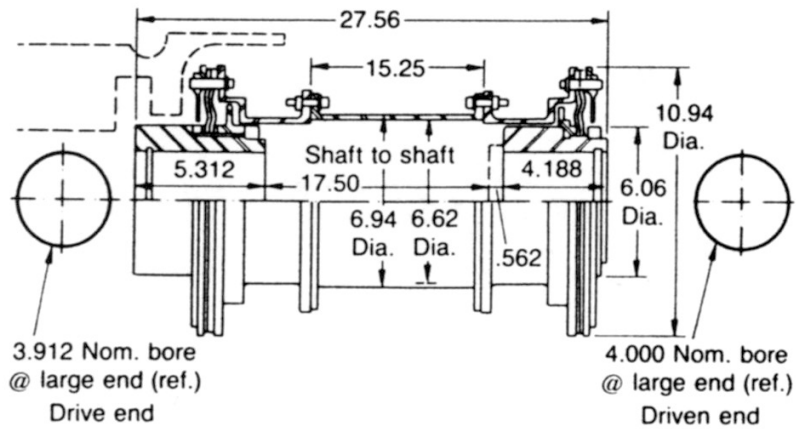


Fig. 13: Position 4 retrofitted diaphragm coupling

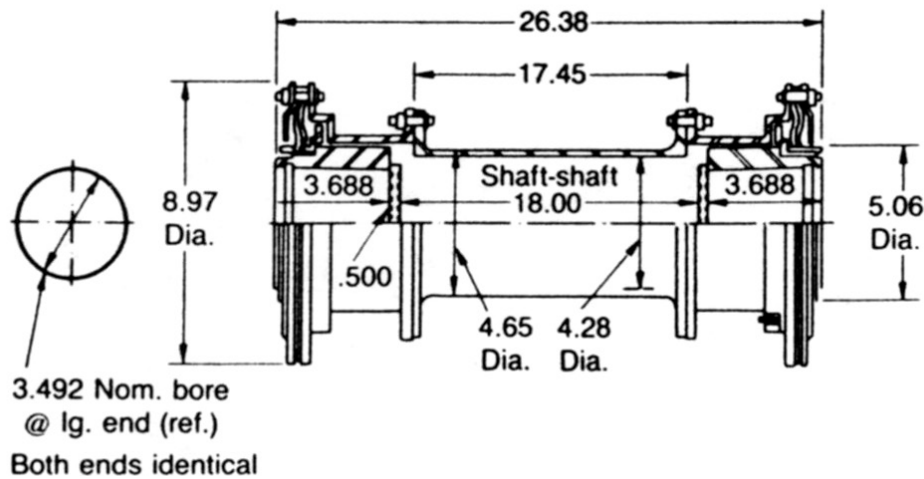


Fig. 15: Position 4 retrofitted diaphragm coupling

- ⑤ Compressor 2BC9-8:
Input horsepower 27,500
Speed 10,300 to 11,000 rpm continuous.
- ⑥ Gear coupling (Fig. 10):
Continuously lubricated/reduced moment design
Size 3
Weight and CG:
Both ends 34.3 lb @ 2.74 in.
Torsional stiffness 5.39×10^6 in.-lb/RAD
OD = 8.2 in.
- ⑦ Compressor 2BF9-8:
Horsepower 13,000
Speed 10,300 to 11,000 rpm continuous.

Retrofit of coupling 1 at position ②: This coupling was retrofitted in 1981 to a tapered contoured diaphragm coupling (Fig.11).

Problems: The diaphragm coupling was substantially larger than the gear coupling. To fit the diaphragm coupling into the unit, the turbine bearing housing was machined from 11 in. to 12 in. It also required machining the housing recess back an extra $\frac{1}{2}$ in. to assure clearance between housing and coupling guard.

Operating experience: No unusual vibration levels have been noted since retrofit. The vibration levels are approximately 1 mil or less. Also, no additional axial vibration has been experienced. The diaphragm coupling has an ANF of 3,900 cpm, which is 2.64 times below the minimum operating speed.

The temperature of the coupling guard is slightly higher than with the gear coupling (130°F with gear coupling versus 160°F with the diaphragm coupling).

Retrofit of coupling 2 at position ④: This coupling was retrofitted in 1986 to a multiple convoluted diaphragm coupling (Fig.13).

| Characteristics | Original cplg (Fig. 8) | Dia. cplg (Fig. 11) |
|---------------------|------------------------------|------------------------------|
| OD (inches) | 7 | 10.9 |
| LP weight @ CG | 30.5 lb @ 2.5 in. | 26.7 lb @ 2.8 in. |
| HP weight @ CG | 30.5 lb @ 2.5 in. | 26.7 lb @ 2.8 in. |
| Torsional stiffness | 3.6×10^6 in.-lb/rad | 3.5×10^6 in.-lb/rad |

| Characteristics | Original gear cplg (Fig. 9) | Diaphragm cplg first proposed (Fig. 12) | Diaphragm cplg installed (Fig. 13) |
|-------------------|-------------------------------|---|------------------------------------|
| OD (inches) | 10.5 | 10.94 | 10.94 |
| HP weight @ CG | 76.7 lb @ 3.19 in. | 61.6 lb @ 3.58 in. | 57 lb @ 2.36 in. |
| Comp. weight @ CG | 68.2 lb @ 2.96 in. | 56 lb @ 3.28 in. | 52 lb @ 3.78 in. |
| Torsional stiff. | 15.4×10^6 in.-lb/rad | 15.6×10^6 in.-lb/rad | 16.3×10^6 in.-lb/rad |

Problems: The retrofit couplings were first proposed using cataloged couplings. After first submission it was found that the proposed diaphragm coupling would interfere with the HP turbine housing. After obtaining the housing layout, it was decided that the diaphragm pack had to be moved forward on the turbine shaft. However, if moved too far, it could have upset the system lateral critical. It was moved forward only enough to provide clearance so that under operation the coupling bolts would not contact the housing (approximately ¼-in. clearance). Calculations were run to determine the heat generated from the nuts against this housing and it was determined that they could generate enough horsepower loss to overheat the coupling guard. So a stepped guard using helicoils was used to reduce the horse-power loss and guard temperature.

Operating experience: No unusual vibration levels have been experienced since retrofit. The vibration levels are lower than with the gear coupling (approximately 25% lower). Also, no additional axial vibration levels have been experienced. This coupling has an ANF of 4,200 cpm, which is 2.44 times below the minimum operating speed. The temperature of the coupling guard is almost identical to what it was with the gear coupling (130°F with the gear coupling, 135°F with the diaphragm coupling).

Retrofit of coupling 3 at position ⑥: This coupling was retrofitted in 1986 to a multiple convoluted diaphragm coupling (Fig. 15).

| Characteristics | Original gear cplg (Fig. 10) | Retrofitted | |
|----------------------|---------------------------------|------------------------------|------------------------------------|
| | | Diaphragm cplg (Fig. 14) | Retrofitted Dia. cplg (Fig. 15) |
| OD (inches) | 8.2 | 10.94 | 8.97 |
| Comp. weight @ CG | 34.3 lb @ 2.74 in. | 55 lb @ 2.74 in. | 31 lb @ 2.97 in. |
| both ends | | | |
| Torsional stiff. | 5.4×10^6 in.-lb/rad | 6.7×10^6 in.-lb/rad | 5.4×10^6 in.-lb/rad |

Problems: The retrofit couplings were first proposed using cataloged couplings. After first submission it was found that the proposed diaphragm coupling was too large for the equipment housing. A maximum coupling diameter of 9 in. was required. A review of the next smaller size showed a maximum bore capacity of 3.25 in. while this application required a 3.492-in. bore, or 1.075 times greater. A review of the coupling design indicated that a change in hub material to 15-5 PH could accommodate the required bore. Catalog coupling hubs were made from 4340 heat treated to 336 to 360 BHN. The increase in strength capacity by using 15-5 PH is 1.4/1.3 or 1.077, thereby allowing the increase in bore capacity.

Operating experience: No unusual vibration levels have been experienced since retrofit. The vibration levels are lower than with the gear coupling (approximately 25% lower). Also, no additional axial vibration levels have been seen. This coupling has an ANF of 5,220 cpm, which is 1.97 times below the minimum operating speed.

The temperature of the coupling guard is lower than with the gear coupling (124°F with the gear coupling, 115°F with the diaphragm coupling).

Summary

When retrofitting gear couplings with diaphragm couplings, time and effort must be allocated to assure that the diaphragm coupling characteristics are closely matched to the gear coupling it is replacing. When retrofits of gear couplings with diaphragm couplings are well thought out, the user can achieve significant improvements in reliability and can minimize downtime due to coupling maintenance problems.

Acknowledgment

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The Author

Jon R. Mancuso is manager of engineering in the Mechanical Drives Division of Zurn Industries, Inc., Erie, Pa., where he has worked since 1966. The author of several articles and papers on couplings for various magazines, societies and symposia, he is also author of the book *Coupling and Joints: Design, Selection and Application*, published in 1986, Marcel Dekker, Inc. Mr. Mancuso has conducted many research and development projects and is coinventor of the "Ameriflex" multiple convoluted diaphragm coupling. He is chairman of the American Society of Mechanical Engineers' Committee on Coupling and Clutches, and member of the Association of Iron and Steel Engineers' Mill Drive Committee, American Petroleum Institute's Committee on Couplings for Special Purpose Applications, and also a member of the American Gear Manufacturers Association Committee on Flexible Couplings. Mr. Mancuso received his BS in mechanical engineering from Gannon University, Erie, Pa. and MS in engineering from Pennsylvania State University.

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