

# COUPLING APPLICATIONS FOR SPECIAL PURPOSE MACHINERY MULTIPLE FLEXIBLE MEMBRANE TYPES

by

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*process data on several centrifugal compressor trains, several machinery uprates beyond vendors previous ratings, and reliability improvements that allow six to eight years of operation between turnarounds. He has been chairman of the Exxon Company U.S.A. Machinery Subcommittee (which represents each refinery), and the Exxon Chemical Americas Machinery Network (which represents each chemical plant), and an active participant in the preparation of several API machinery standards. He is presently part of the Mechanical Services Compressor Section team which consistently achieves 99.96 percent reliability on 15 large compressor trains.*

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## INTRODUCTION

Special purpose machinery applications of flexible disc couplings with multiple convoluted diaphragms or disc packs at each end of the spacer are discussed. Couplings in this category were retrofitted on two compressor trains at a large ethylene plant. The couplings were a 44,000 hp multiple convolution flexible disc coupling and a 25,000 hp bolted disc pack flexible disc coupling.

The installations were retrofits, as part of a program to uprate the compressor trains beyond the original mechanical ratings, at a minimum cost and with limited machine downtime. The user had overall engineering responsibility for selection of the type of coupling, and performance of the total installation. Selection of the coupling type, coordination meetings, design audits, quality control and installation procedures, and contingency plans were done with the full cooperation of the coupling, compressor, and turbine vendors. This resulted in uprating the trains with a high degree of reliability made possible by the careful application of these types of couplings.

Based on experience gained from these installations, the following are problem areas:

- Multi-convolution coupling application
- Disc pack coupling application

- Specification items to supplement API-671
- Design audit and tests
- Quality control and installation procedures

These comments are meant to convey experience with specific flexible membrane couplings, and to suggest considerations that may be applicable to them, and not to exclude other vendors, designs or circumstances that may be available or may result in different decisions or selections.

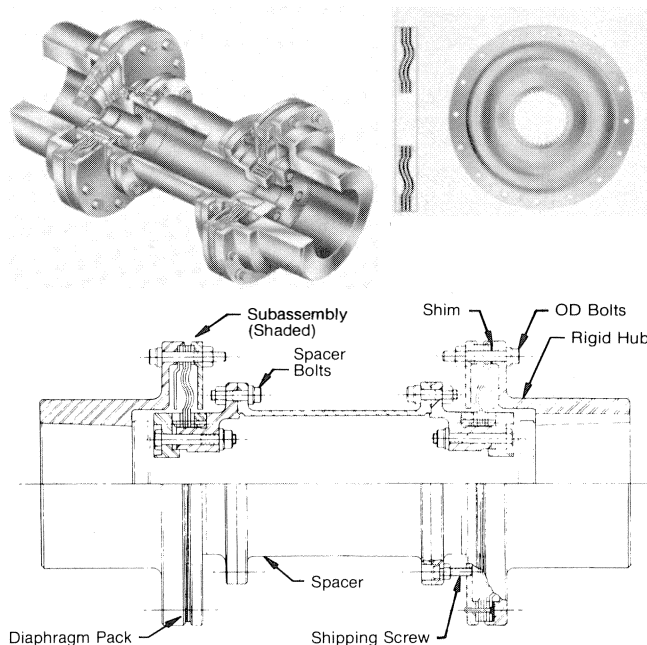


Figure 1. Multiple Convolution Flexible-Disc Coupling (Zurn Industries' Ameriflex).

## DISCUSSION

### Multi-Convolution Coupling Installation

Use of a multiple convoluted diaphragm coupling (Figure 1), plus other modifications, allowed an increase of more than 20 percent in the allowable transmitted horsepower (to 44,000 hp in one train). Previously the train was limited by the original gear type coupling, shaft stress, and thrust bearings. The coupling also allowed longer run times, by removing the constraint of gear coupling sludging.

The following basic advantages of the flexible membrane coupling that was used are:

- Axial loads transmitted are much less than for a gear type coupling. This greatly reduces thrust bearing loads.
- Since no lubrication is required, coupling teeth sludging and wear problems are eliminated, and run durations are increased.

- Less bending loads are transmitted, thus reducing shaft stresses. This also reduces startup vibration due to misalignment.

- Absence of radial clearances throughout the major components makes it possible to obtain a precision repeatable balance.

In addition, the following considerations were applicable to this coupling:

- The *multiple* flexible diaphragm design tends to provide a lower disc stress level for a given diameter.

- There is no reason a properly applied coupling should fail. However, if there were a diaphragm failure, an outer diaphragm would be expected to fail first, because it has the highest stress from large misalignment. The lower misalignment stress on the remaining diaphragms may allow continued operation for a period of time, without the failure progressing to the total separation of the coupling.

- The convolution feature should allow increased axial movement for a given size coupling.

- The convolution feature should allow more misalignment capability and reduced bending stress for a given size coupling.

- The convolution feature should provide a linear axial stiffness and deflection, and a single axial natural frequency throughout the rated axial position range.

- Separation spacing of the multiple flexible diaphragms does away with the question of possible fretting corrosion between the discs.

- This type coupling has had numerous successful applications in high horsepower services. It was not considered necessary to conduct additional full scale tests to have a high degree of confidence in this coupling.

#### Disc Pack Coupling Installation

Use of a disc pack coupling (Figure 2), plus other modifications, allowed a train to withstand an increase of more than 30 percent in the transmitted horsepower (to 25,000 hp). This system was previously limited by the original gear type coupling, shaft stress and thrust bearings.

The retrofit coupling has the four basic advantages of a flexible membrane coupling. In addition, the following considerations also are applicable to this coupling:

- The multiple flexible disc design tends to provide a low disc stress level for a given diameter.

- There is no reason a properly applied coupling should fail. However, if there were a disc failure, an outer disc would be expected to fail first, because it has the highest stress and tendency for fretting from large misalignment. The lower misalignment stress and fretting tendency on the remaining discs may allow continued operation for some time, without the failure progressing to total separation of the coupling.

- The coupling readily adapts to a reduced moment design by complete freedom in the location of the hub flanges on the hubs. This was a definite advantage, because an increase in the overhung moment was not desirable. Also, the reduced moment design increased the effective spacer length, and allowed the design to be based on a smaller misalignment angle.

- Interchangeability of the disc packs, and the shop component and assembly balance of the main coupling and spare couplings, allowed the disc packs from the spare coupling to be installed in the field without changing the hubs, and without adversely affecting the assembly balance. This was proven when the disc packs were actually changed in the field.

- In order to establish a very high degree of confidence with this disc pack design for long term operation with the high

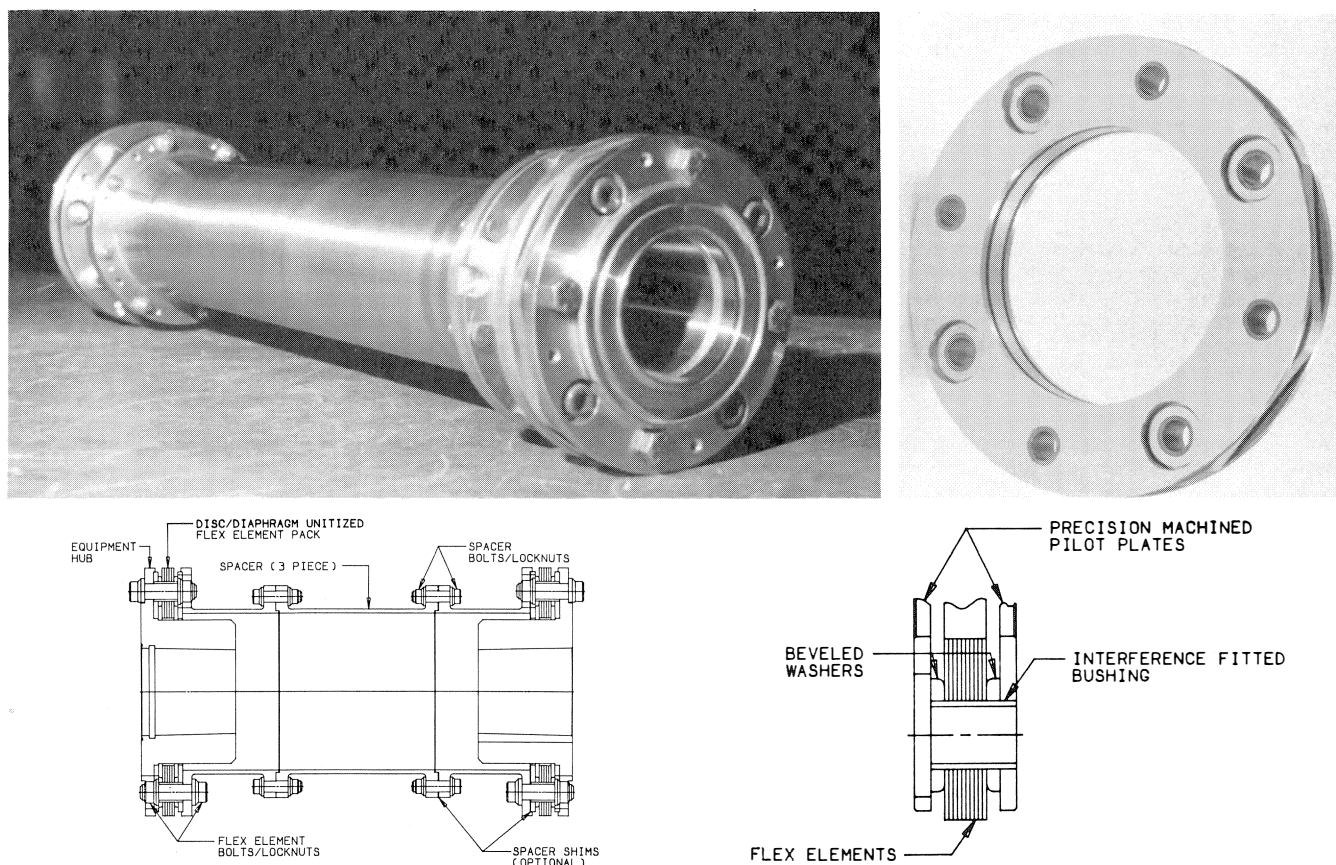


Figure 2. Bolted Disc Pack Coupling (Rexnord, Incorporated's Thomas).

loads specified, a misalignment and torque load full scale test of this disc pack design at abnormal conditions was conducted. The relatively small size of coupling for the required operating torque (228,000 in-lb) was the result of a small shaft diameter on the compressor (4 in), a low overhung weight and moment requirement, and limited available space.

- Design of the coupling facilitates visual examination of the disk packs.

#### *Specifications to Supplement API-671*

The following considerations may be helpful to supplement the specification in API Standard 671, Special Purpose Couplings for Refinery Services, First Edition, December 1979.

API 671 paragraphs 2.1.1 and 2.3.3 require, unless otherwise specified, that coupling designs permit:

- Continuous operation at 175 percent of purchaser-specified maximum continuous torque.
- Operation without damage at 115 percent of purchaser-specified maximum transient torque.
- Continuous operation at 125 percent of purchaser-specified axial displacement, angular misalignment and parallel offset, occurring simultaneously.

The complexity and interdependency of factors affecting the coupling design required a detailed engineering effort to establish the design basis. Even though the driver and compressor vendors provided some data to help develop the purchaser specified values, it was necessary to work with the coupling vendor to set the purchaser specified design basis, and to select a coupling with a factor of safety to allow for future maintenance and operation variables that could affect the design basis.

The maximum continuous operating torque basis should allow for present and future conditions; however, the API requirement is interpreted to mean 175 percent of maximum torque, simultaneous with application of 100 percent of the maximum specified axial displacement, angular misalignment and parallel offset. The coupling design should consider resultant flexible membrane stress from actual combinations of conditions that may occur simultaneously. For example, the coupling could possibly see a larger than 25 percent misalignment or axial position variation because of an installation error. It is desirable to design the coupling to allow for these. However, it is unlikely that extremes of both would occur simultaneously. Purchaser specified maximum conditions have to provide a balance between the possible extremes of field conditions and what is practical for each vendor to provide.

Reducing stress from one condition does not necessarily allow a corresponding increase in stress from other conditions. Increases in alternating stress from misalignment is much more severe than increases in steady state stress from torque or axial position, up to a critical limit of axial position. In areas where there may be vulnerability, such as axial position design constraints, specific field procedure requirements must be established and enforced.

The vendor should be asked to provide data on the factor of safety on membrane stresses (steady state and fatigue) for the API specified combination of purchaser specified conditions, and for larger amounts on each variable, when the other conditions are normal. Catalog ratings are not necessarily a substitute for factor of safety data based on the predicted stress and its verification by actual shop or field test data. Specification requirements that the vendors' "coupling design shall permit continuous operation" at the purchaser specified design conditions could encourage vendor to reduce the factor of safety in their catalog ratings. A review of vendors' design criteria and test data on flexible membranes, together with

specific field experience with known stress and potential fretting conditions, is more important than catalog data alone for the coupling design basis and factor of safety determinations for each type of stress.

The transient torque (API 671 Paragraph 2.1.1) should include an allowance for motor starting and reacceleration torque, compressor surge, and possible liquid carryover into a machine. Even though the intent is to provide a large factor of safety, it may be more prudent to design the coupling diaphragm to fail or hub-to-shaft juncture to slip before a shaft or other catastrophic failure. Of course, every practical effort should be made to reduce the probability and severity of transient torques because of the possibility of damage that could require replacement of the shaft hub if there is slip. Suction drum high level automatic shutdown, fast response compressor antisurge controls, electrical design to limit reacceleration torque, and/or high vibration automatic shutdown are some methods to limit transient torque loads.

Several considerations may affect the axial position design basis (API 671 Paragraphs 2.1.3 and 2.3.7). Expansion data provided by the turbine vendor was a number giving the maximum possible axial movement for the turbine. This value, however, did not fully show the effects of casing movement and the normal operating axial position of the coupling. Therefore, an estimate was made of the normal position of the turbine to use to select the axial shims that produced the least amount stress on the flexible membrane couplings. In addition, the design was checked for the maximum possible deviation from this position in each direction for the design basis.

When the compressors were shut down for coupling installation, the actual between shaft ends dimensions were checked and found to be different from that shown on the original drawings. One compressor casing had to be moved slightly, and the axial shim thickness had to be adjusted for both couplings based on actual between shaft end dimensions and the actual coupling hub pull-up on the tapered shaft ends. Specifying a larger than standard shim size allowance prevented what otherwise could have been very time consuming problems.

Factors that may affect the axial position are:

- Thermal expansion or contraction of rotors, after considering the effect of the location of the thrust collar, expansion or contraction of the casing, location of the fixed ends of the machine, and the machine operating conditions, such as both maximum and minimum extraction for steam turbines.
- Design and actual setting of the thrust collar locations on shafts, thrust bearing dimensions, and shaft axial dimensions.
- Location of machine casings, and between shaft end dimensions, as actually installed. For a retrofit, this was found to be different than shown on original drawings, because it had not been critical for the original gear type couplings.
- Coupling hub pull-up on shaft ends.
- Axial shims installed as a part of the coupling. API 671

Paragraph 2.3.7 requires a variance of one-eighth inch for up to four inch diameter shafts and one-fourth inch for four inch and larger shafts. Shim sizes may be changed to allow more than the minimum variances, and to provide more exact positioning by use of a combination of thinner shims than normally furnished. One vendor provides a peelable shim to provide the exact axial position desired. Bolt lengths and other dimensions should be checked, if thicker than normal shims are used.

Items that affect misalignment (both angular and parallel offset) are important to the design basis, field installation and maintenance checks. Even though flexible membrane couplings are generally tolerant of significant misalignment from vibration and shaft bending stress considerations, the actual stress in the flexible membranes increases with misalignment.

An error in misalignment settings or alignment changes from foundation settlement or pipe loads, could result in high stresses on the flexible membranes without the easily noticeable increase in vibration that would be expected on a gear type coupling. Therefore, two precautions were taken:

- The coupling selection was based on a conservative design that would provide a large allowance for misalignment with the existing spacer length.
- A program of hot alignment checks was instigated to verify the actual alignment at initial operating conditions, and periodically in the future to ensure that there are no unacceptable alignment changes due to casing distortion from pipe shifting or other unknowns. The Essinger Bar system was used for this purpose.

The axial natural frequency is determined by the fixed mass of the spacer element and the axial spring rate of the membranes (API 671 Paragraphs 1.4.3 and 2.3.4). Since the spring rate varies with axial position on disk pack type of couplings, the possible variances in actual position discussed previously should be considered when determining the range of the natural frequency. For this calculation, it may not always be practical to include extremes of axial position that only occur at startup and other rare occasions. Another question is whether axial natural frequency test data, without torque and other operating stresses, requires a correction, when the operating torque stress is applied. Tests on the full size disc pack coupling showed that no correction was required for torque.

Bolting for multiple flexible membrane couplings is critical and requires special attention. API 671, Paragraphs 2.1.11 and 3.6, provides some bolting considerations and specifies a minimum of SAE J 429h Grade 5 bolts or better. Because of previous bolt failures on several types of couplings, it is suggested that bolting be purchased and tested to military or other equivalent specifications for manufacturing procedures and quality control. It is also suggested that ten percent surplus of bolts be specified, to allow for possible destructive testing and/or replacement of lost or damaged bolts. Bolts for spare couplings should be the same weight and dimensional tolerance as those for the primary coupling.

To take full advantage of high ratings possible with flexible membrane couplings, where the shaft diameter cannot be increased, coupling hub and hub to shaft junctures may be the design limitation, and may have to be given special consideration. Hydraulically fitted, keyless hubs can provide high ratings. However, the minimum interference fit of 0.0015 in per inch of bore diameter specified by API 671 Paragraph 2.1.7.4 provides only limited rating capability. Potential ratings increase with tighter fits. The hub design calculations should be checked for installation, removal, and transient torque condition stresses when tighter fits are used. Finite element analyses of the hub designs resulted in changes in the hub materials and to the dimensions on both of the couplings because of limitations due to the shaft diameters.

#### *Design Audit and Tests*

In order to verify a vendor's flexible membrane designs, a three step program was developed to:

- Review vendor design test data, calculation basis and factor of safety, and field service experience of couplings in service.
- Review results of a destructive testing program involving several small couplings, and extend the program to provide additional testing. This program had been initiated in an attempt to monitor the progression of membrane overload failures, by means of acoustical signal transmission.
- Provide a load test of the 25,000 hp rated disc pack coupling for three months at a gross misalignment. This was followed by a static torque load test above catalog design

rating. The test was specified to establish a very high degree of confidence for long term operations without inspection. The present design basis is eight-year run durations between inspections.

The review of the vendor design basis and experience generally indicated adequate factor of safety allowances for possible fatigue and combined stresses. The failure mode from gross misalignment was predicted at an outer flexible membrane. It was considered possible that under some conditions the coupling might operate indefinitely with a damaged outer membrane, because misalignment stress would be reduced with a thinner effective diaphragm or disc pack.

For the very high loading on the relatively small size disk pack coupling on the 25,000 hp turbine, there was a question on the bolt clamping forces required to carry all of the torque in friction, and not by edge loading of the discs on the bolts. For this reason, bolts of higher strength than the vendor's standard bolts were specified for this service.

A study evaluated consequences of flexible membrane coupling failures on turbine drivers, and possible methods of detection and limitation of damages. It was concluded that currently available instrumentation, such as acoustical detection techniques, is not a practical, dependable way to monitor and detect membrane deterioration in service or incipient failure. The stresses needed to cause failure of the several types of small test discs (both multi- and single-membrane types) confirmed the manufacturers claims of conservative ratings. Therefore, with proper attention to coupling application, installation and maintenance, the possibility of a failure is extremely small. This is verified by the excellent operating experience of many couplings in service for several years.

As additional insurance items, attention should be given to other items in the compressor trains, such as steam turbine governor and trip systems. API 612, Special Purpose Steam Turbines (1979 Revision), Paragraph 3.2.2.4, requires that governor systems be designed to control upon instantaneous loss of load. This is interpreted to include a coupling disconnect failure. This could happen with less advance warning on a flexible membrane coupling than on a gear type coupling (and with even less warning on a single flexible membrane coupling). Therefore, the couplings were selected to provide the largest practical factor of safety in stress levels, even if this resulted in a larger size coupling than allowed by catalog rating data. Other factors that warrant attention are electronic governors and relays for faster control response, if there should be a disconnect, electronic overspeed trip systems, provision to close the governor valve in addition to the trip valve in an emergency, and close coupling of the trip valve to the turbine to reduce downstream steam stored energy.

The load test of the bolted disc packs included:

- A high misalignment load (150 percent of catalog rating = 0.38 degree) and 16 percent of the maximum continuous torque on one disc pack.
- A high torque load (95 percent of catalog rating = 40,000 in-lb) for the reduced number of discs in another disc pack and a 0.38 degree misalignment (60 percent of catalog rating) for this pack.
- Operation for  $59 \times 10^6$  revolutions.
- A static load test of 2.5 times the maximum continuous torque (rated peak torque) on the first disc pack, and 3.8 times the maximum continuous torque on the reduced number of discs in the other disc pack.
- Axial resonant frequency measurements ranging from 115 to 155 Hz for the composite coupling at the allowable axial position variations.

This test work verified our high confidence level in these disc packs.

Some of the quality control and installation procedures used for these couplings were:

- Special efforts to component balance, and assembly check balance without having to add balance corrections, proved successful. However, this did require several days to accomplish. Different vendors used different balancing techniques and tolerances. Rotating parts 180 degrees for checking for balance resolved questions of whether parts were properly centered when balanced on a mandrel.
- In order to provide accurate rolling surfaces for assembly balance check, the tolerances on the hub rolling surface was limited to 0.0003 in total indicator runout.
- Concentricity of critical fits that affect balance were verified.
- Hub to shaft fits were verified before the field installation, by use of plug and ring gages.
- Ability to install and remove hydraulically fitted hubs with tight interference fits was verified on dummy shafts, before the actual field installation. Procedures were developed to provide gradual cooling, to prevent distortion after the hubs were heated for installation.
- Bolt lengths had to be verified and/or adjusted to accommodate larger axial position adjustment shims. Inspection of bolts included checking of the body fit bolt the diameter, fillet at the head, the chamfered edge of the surface at the hole where bolt is to be inserted, bolt balance, nut balance, review of the certification of bolting material, plating and treatment after plating to avoid cracking caused by hydrogen embrittle-

ment, verification of the military specifications and tests performed and destructive testing of a sampling of special high strength bolts.

- Bolt assembly torque requirements for lubricated and non-lubricated plated bolts were verified by tightening sample bolts and measuring elongation.

## SUMMARY

Coupling design, installation and maintenance requires careful attention to ensure reliability intended for special purpose machinery. A flexible membrane coupling provides important advantages including reduced thrust bearing loading, increased run durations resulting from no gear teeth wear or oil sludging, reduced shaft stresses and misalignment forces, and precision balance. However, it is necessary to ensure that limitations, such as limits for the axial movement, are observed. In order to develop the purchaser specified conditions listed in API 671, it is necessary to have an understanding of each vendor's coupling ratings and limitations of his designs. Since machinery gross misalignment and the related high stress of flexible membranes may not show up as vibration on monitoring systems to give advanced warning of an impending failure as normally seen with a gear type coupling, care should be given to the alignment basis and on line alignment checks. The objectives were to select couplings with a large factor of safety for all possible stresses, and to develop specific installation and maintenance procedures for the couplings selected.

