Experiences with Flexible Couplings on High Speed Boiler Feed Pump Drives

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SYNOPSIS

In recent years the powers absorbed by and speeds of boiler feed pumps in C.E.G.B. power stations have increased substantially. Current designs require powers up to 17 MW at speeds up to 7,500 rpm. At lower power just below 8 MW one pump runs at 8.650 rpm. While earlier pumps absorbing about 12 MW relied on gear type couplings many of the latest feed pumps use multi-pack membrane or contoured disc couplings. Accordingly operational experience in the C.E.G.B. covers all 3 types and this is reviewed in this paper: the advantages and disadvantages of each type are assessed.

Additionally a number of specific problems that have occurred with the couplings on feed pump drives are described with the means of their solution.

Introduction

In recent years the CEGB has standardized firstly on 500 MW turbo-generator units and more recently on 660 MW units. All of these units have a main turbine driven boiler feed pump and usually two 50% duty motor driven boiler feed pumps for starting purposes and standby requirements. In most cases a booster pump is coupled in line, running at lower speed than the pressure stage pump. With turbine driven pumps the turbine is directly coupled to the pressure stage pump. A gearbox is provided for the lower speed drive to the booster pump; on the 500 MW units these two items are connected to the pressure stage pump: on the 660 MW units they are connected to the turbine. On the motor driven pumps the booster pump is usually direct coupled to the motor with a rotational speed just below either 1,500 rpm or 1,000 rpm; the pressure stage pump is driven from the opposite end of the motor through a gearbox – of the epicyclic type on the 500 MW units and of the parallel shaft type on the 660 MW units. A typical motor driven boiler feed pump installation is shown in Figure 1; this is a starting/standby pump at the CEGB power station at Fawley, where the units are rated at 500 MW. All the various components on all these units are connected with the flexible couplings. This paper is concerned with the high speed couplings on these pump units together with similar ones on the pumps on the 350 MW units at Tilbury ‘B’, since our experience with these have a number of features of interest. Typical speeds and ratings are shown in Table 1.

Table 1

Boiler Feed Pump Powers and Speeds

Station	Turbo-Generator Unit Size MW	Pump Main (M) Or Standby (S)	Power MW	Speed Rpm
Tilbury ‘B’	350	M (units 8-10)	8	4750
“	“	M (unit 7)	8	8650
“	“	S	4	6721
West Burton	500	M	12	3300
“	“	S	6	4800
Fawley	500	M	12	4150
“	“	S	6	5588
Cottam	500	M	12	5000
“	“	S	6	6000
Drax	660	M	17	7500
“	“	S	9	8000
Hinkley Point	660	M	13	4900
‘B’	“	S	7	6700
“ “ “				

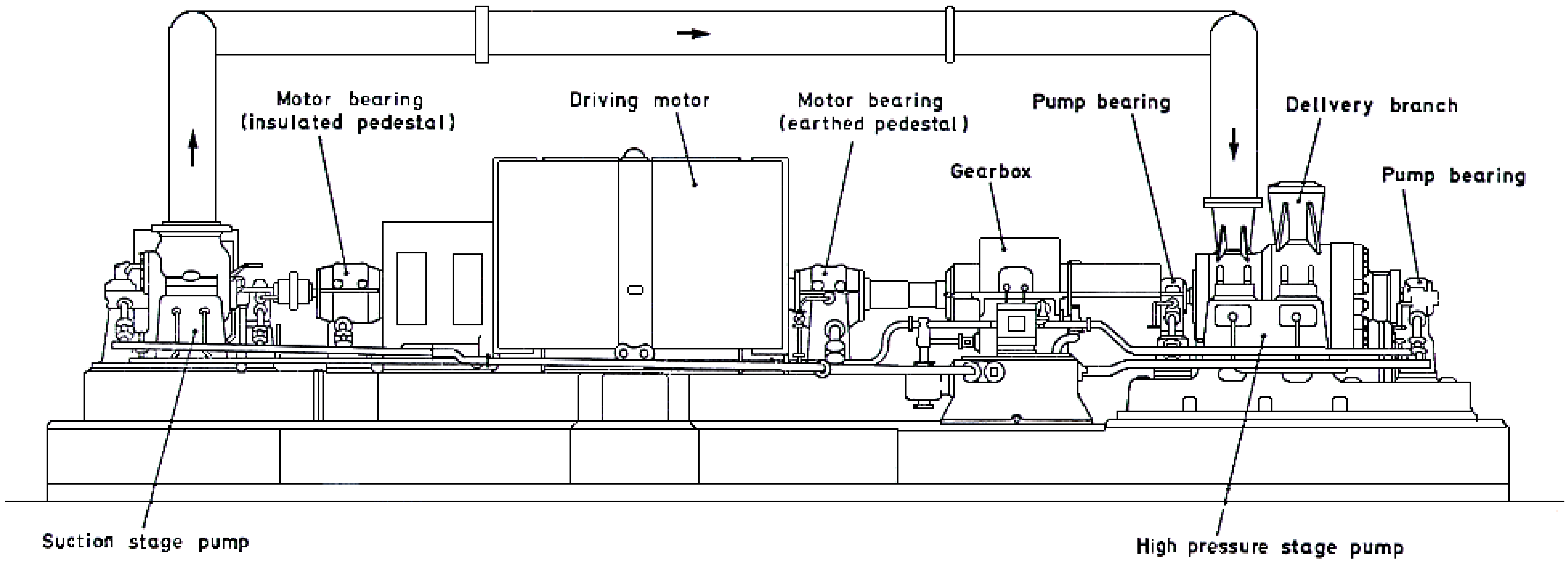

Fig. 1

Typical motor driven boiler feed pump installation

Fawley Power Station

At Tilbury ‘B’ and on all the 500 MW units the high speed couplings on the motor driven pumps are of the gear type with one exception referred to later in Section 6.3. The earlier main pumps on these units also use gear couplings but a number of the later ones have multi-pack membrane couplings. On the 660 MW units the motor driven pumps usually have multi-pack membrane couplings and the main pumps either membrane couplings or contoured disc couplings.

On typical boiler feed pump drives the couplings should be capable of accommodating transverse misalignments of 0.5 mm and axial displacements of ± 3 mm. The requirements may vary from these typical values for some installations. On the older designs of feed pump using balance discs for thrust balance the required axial displacement may be greater to allow for balance disc wear.

GENERAL OPERATIONAL EXPERIENCE

The first 500 MW units went into service 11 years ago and so substantial running hours have been accumulated on the pumps and their couplings, in many cases around 30,000 hours with some pumps having run even longer.

Normally the pumps with the greatest operational times are main turbine driven pumps; in many cases the motor driven pumps only run a few hundred hours a year. However, a few motor driven pumps have run for substantial periods, reaching up to 30,000 hours. Generally the experiences with all types of couplings on these feed pumps have been very good, but there have been a number of cases, where there have been problems, some of which are referred to later in this paper in Section 6. The different types of coupling are each examined in turn.

GEAR COUPLINGS. DESIGN FEATURES AND OPERATIONAL EXPERIENCES

Typical gear couplings on the main drive of main boiler feed pumps are shown in Figures 2 and 3. Figure 2, is that used at Tilbury ‘B’ power station and Figure 3, at West Burton power station. Couplings for motor driven feed pumps are shown in Figure 4. These are both for Tilbury ‘B’ and the differences are discussed later in Section 6.1.

Continuous oil lubrication is provided. This is absolutely essential at the speeds and powers transmitted. The two types have different oil feed arrangements. The West Burton main pump type and the motor driven types both have oil feeds to the centre of every tooth. It is often argued that this is the preferable arrangement. In practice the alternative method of end feeding as used on the Tilbury ‘B’ main pumps seems to works just as well and we have no particular preference.

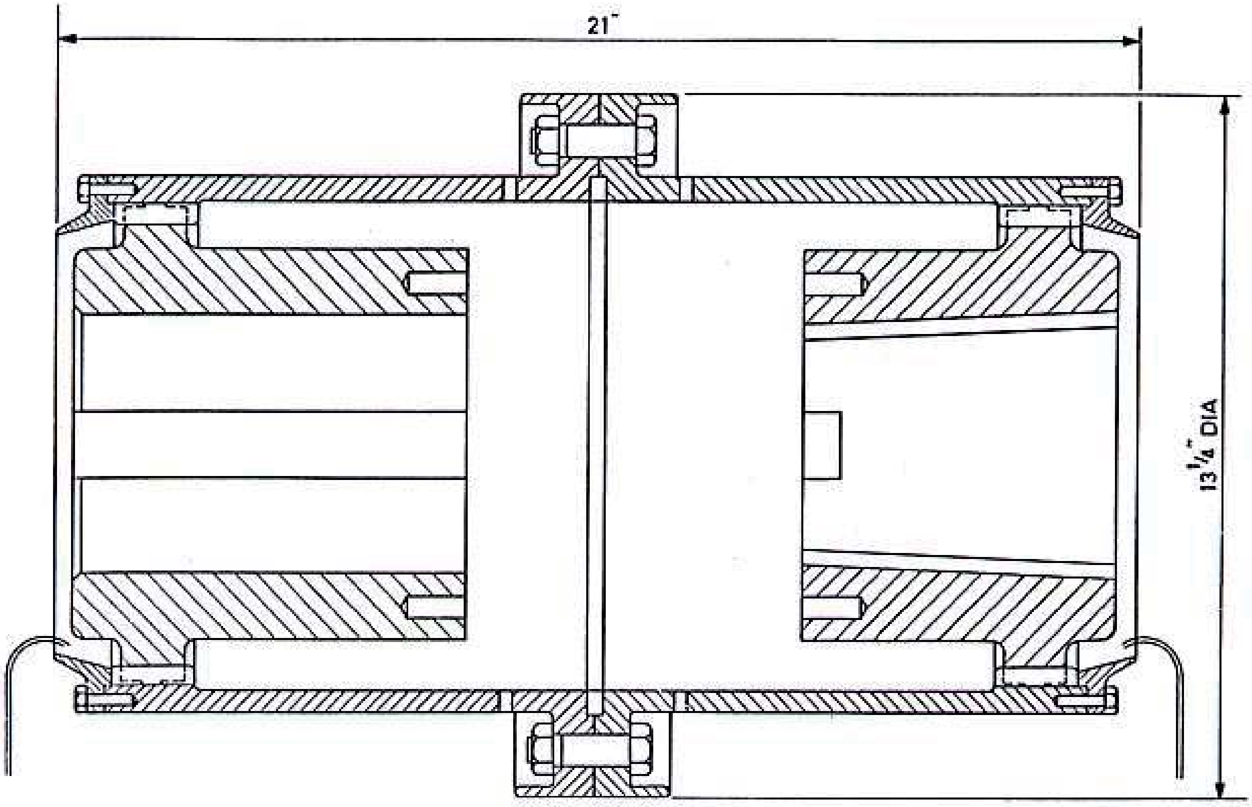

Fig. 2

Typical gear type couplings on main boiler feed pump drives
Tilbury B Power Station

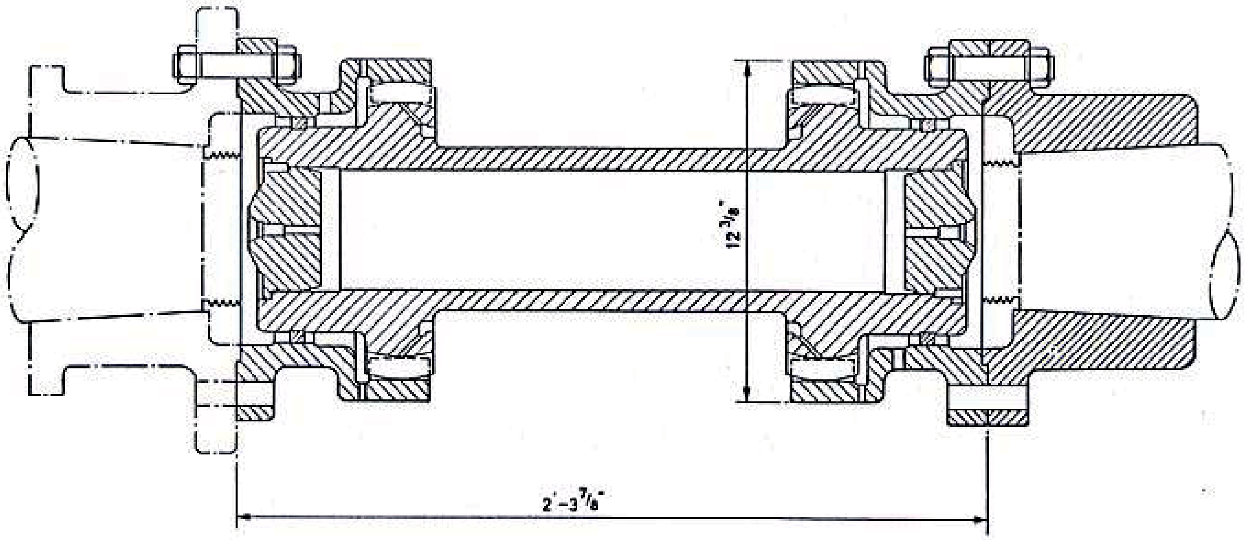

Fig. 3

Typical gear type couplings on main boiler feed pump drives
West Burton Power Station

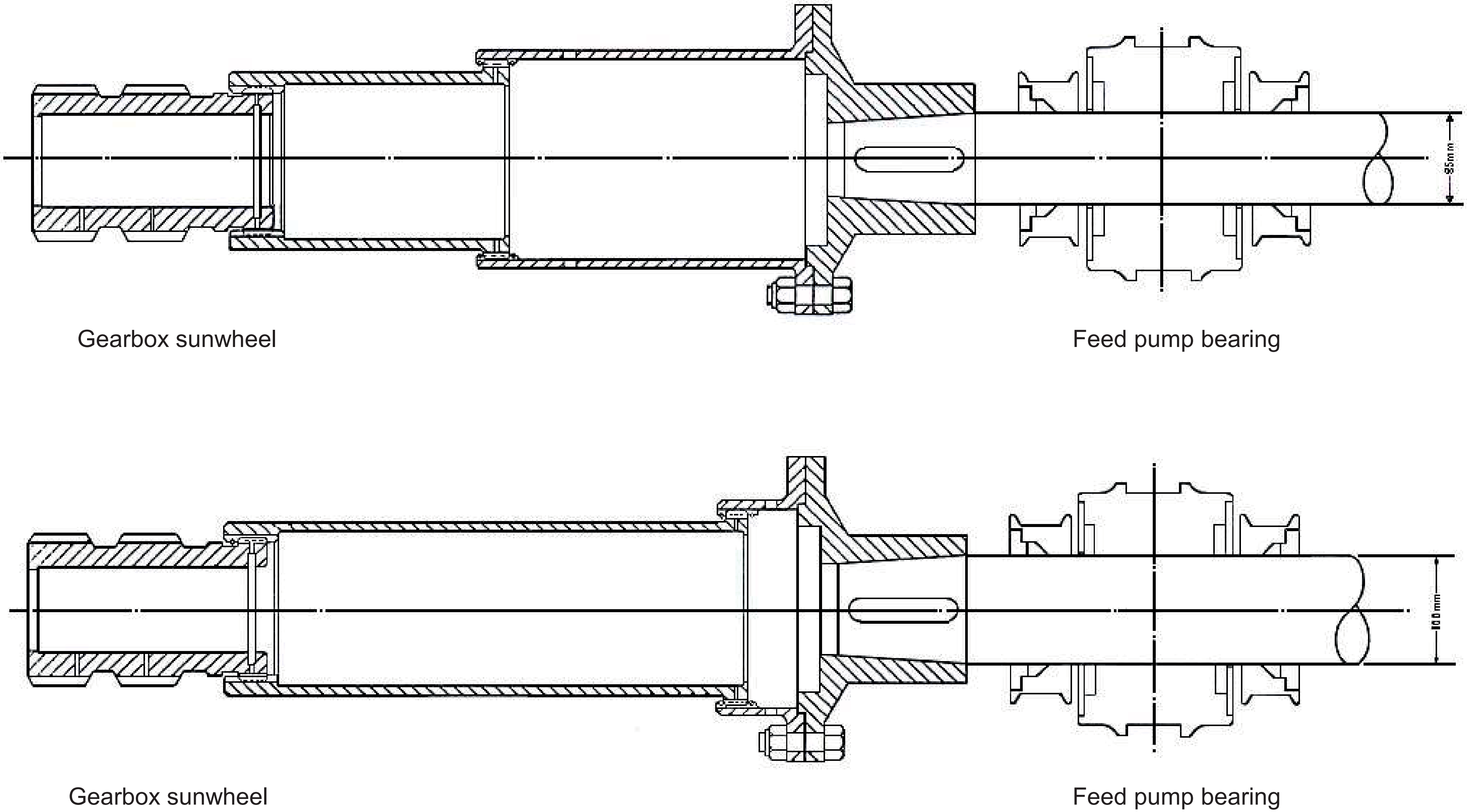

Fig. 4

Original (top) and final (bottom) arrangements of coupling and feed pump shaft

Tilbury B starting / standby pumps

Whichever type of feeding is used no dams are provided on the outlet side. I am sure that this is correct for high speed couplings. Bearings and gearboxes cannot accept interruption of oil supply and will fail more rapidly than the couplings if the supply ceases. Accordingly the units must be tripped on complete loss of lubricating oil supply. If dams are provided, impurities will be centrifuged out and remain in the coupling, where they may disturb the balance and ultimately block the passage of the oil; for this reason they are undesirable.

General dynamics of the shaft systems require that the pivot planes should be as close to the bearings as possible. This requirement also applies to membrane and contoured disc couplings. For this reason the arrangement of the Tilbury main pump is preferable to that of the West Burton type provided the speed is not to high that the permissible sliding velocity becomes limiting – this is considered further in Section 6.4 – or that the stresses in the spacer sleeve become excessive.

With continuous spray lubrication on gear couplings and forced lubrication bearings, which latter are standard on CEGB boiler feed pumps, there is no need for oil throwers between couplings and bearings and these should be eliminated, so enabling the pivot planes to be even nearer the bearing.

At CEGB stations most feed pump units and hence the gear couplings are overhauled every 2 years; in a few instances couplings are examined annually. Where little running is done on motor driven standby pumps, the interval may be longer. Normally a general clean up and check that oil ways are clear is all that is necessary before returning the couplings to service.

As a general rule site balancing after installation has not been found necessary with gear type couplings.

In many cases on 500 MW units the coupling between the pressure stage pump and gearbox is a gear coupling transmitting much less power than the main coupling to the driving turbine but sill running at pump speed – between 4,000 and 5,000 rpm. The power transmitted is about 900 kW. Most of these couplings started as grease filled. At these speeds there has been considerable difficulty in retaining the grease in the coupling. Various modifications have been tried to improve the grease retention but it is still necessary to check them every 3 months. At Didcot power station all these couplings have been converted to continuous spray lubrication; this is a simple modification and it appears to be fully successful although, at the time of writing, the longest running modified coupling has only been in operation for 8 months. This modification has been recommended for all these high speed grease filled couplings at other CEGB power stations.

It has sometimes been argued that gear couplings can lock and then give a sudden release with a substantial axial movement, which may cause internal damage to components of a feed pump such as the balance disc. For a gear coupling in reasonable condition this argument is not supportable. To hold a feed pump balance disc off balance requires an axial force of about 300,000 – 400,000 N. With an effective coefficient of friction of 0.15, the axial friction force that a coupling would sustain would be about 40,000 N. In practice due to the rocking action of the coupling the effective coefficient of friction will often be less; see Boylan (Reference 1). For the coupling to hold the balance disc off would require a coefficient of friction in excess of 1; this would require the coupling to be extremely badly worn. Accordingly alternative explanations must be sought for the so-called “locking”. A possible explanation is that the shaft may become bowed while standing and be held axially internally; the “lock” is then released when the shaft has straightened.

MULTI-PACK MEMBRANE COUPLINGS. DESIGN FEATURES AND OPERATIONAL EXPERIENCE

Typical multi-pack membrane couplings used on main boiler feed pumps are shown in Figures 5 and 6. Figure 5 is from Fawley and Figure 6 from Pembroke. Nearly all the membrane couplings used on the CEGB feed pumps are of the type where the torque is transmitted tangentially with the membranes clamped by bolts alternatively to the driving and driven hubs, although in a few cases the drive is through radial membranes. 4, 6 or 8 bolt couplings may be used. Currently we are tending to eliminate the 4 bolt couplings from high speed applications.

Although most of our membrane coupling installations on feed pumps have more features in common with the Pembroke design, an examination suggests that the Fawley design may have two advantages. Firstly by locating the membranes over the hubs, the pivot planes are nearer the bearings: this means that balance will be less critical and it has not been found necessary to site balance the Fawley couplings on rebuilding a pump unit or changing a pump cartridge; with most of our feed pump installations with membrane couplings site balancing is necessary. Secondly provision for adjusting the length of the coupling is provided. At Fawley the axial gap between the main pumps and their driving turbines varies by 12 mm over the 4 units. Since one of the main limitations of membrane couplings is their permissible axial expansion, this feature is useful and necessary.

Like gear couplings membrane couplings on feed pumps are normally examined every 2 years. Provided there is no sign of distress they will be reinstalled for a further similar period of operation.

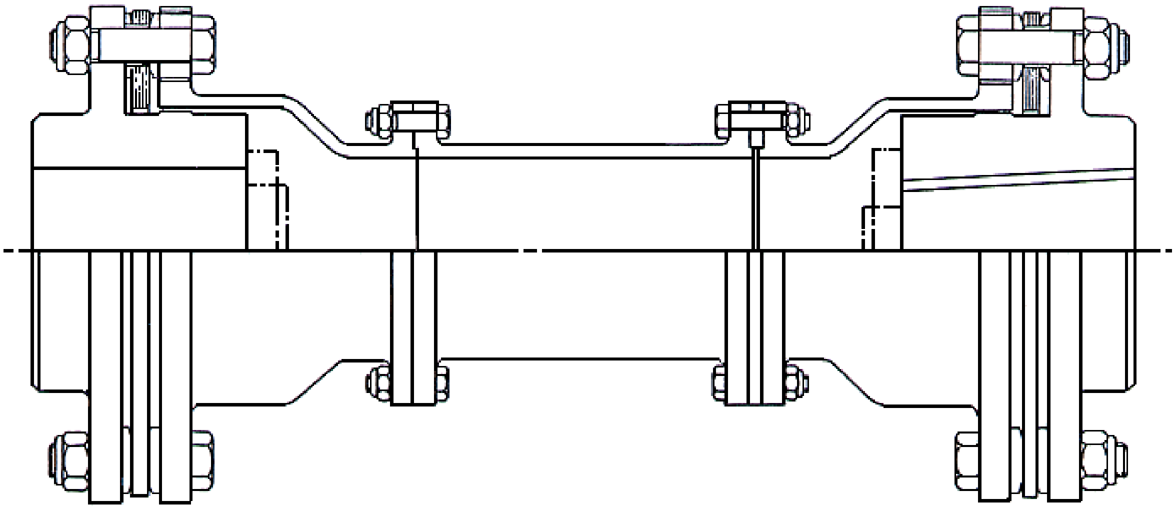

Fig. 5

Membrane coupling. Fawley main boiler feed pump

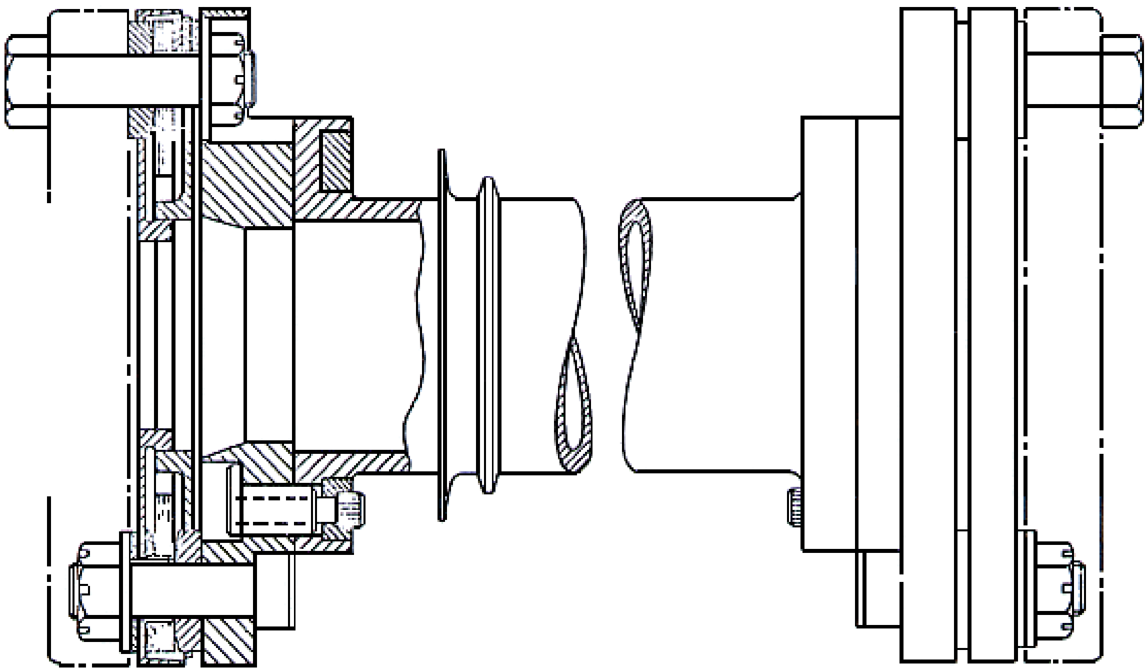

Fig. 6

Membrane coupling. Pembroke main boiler feed pump

CONTOURED DISC COUPLINGS. DESIGN FEATURES AND OPERATIONAL EXPERIENCES

A typical contoured disc coupling on a boiler feed pump drive is that for a Hinkley Point 'B' main boiler feed pump shown in Figure 7. This example includes an optical torquemeter, which are sometimes included.

CEGB operational experience of these couplings on boiler feed pump drives is currently rather limited – about 40,000 hours total on 4 couplings - although a number are fitted on plant being installed. 3 of those in service have run very satisfactorily. The fourth failed in service; this coupling had for a time run with an axial displacement grossly above its design value and also survived two pump seizures, but failed shortly after the second seizure; the design therefore cannot be faulted on this account. However, the fact that it had been operated above its design axial displacements does stress the need for the axial displacements to be carefully assessed for contoured disc couplings – and for membrane couplings too.

With these contoured disc couplings site balancing has been found necessary after changing a pump cartridge and check balances are carried out after disturbing the couplings.

SPECIFIC PROBLEMS WITH COUPLINGS

Although the current experience of the CEGB with high speed and high power flexible couplings has generally been very good, we have had a number of problems with them during the past 10 years. It is useful to review a number of these and look at the lessons that have been learnt from them.

Tilbury 'B' Starting/Standby Pumps

At the time that the starting/standby pumps at Tilbury 'B' power station were commissioned about 10 years ago they were among the highest speed machines operated by the CEGB, with a maximum running speed of 6721 rpm. As originally built they were prone to vibration in the high speed components – the gearbox, coupling and boiler feed pump. The original design of the drive end of the boiler feed pump shaft and coupling together with the sun wheel of the adjoining epicyclic gearbox is shown in the top half of Figure 4, and the final version in the lower half. In this condition with the reduced overhang to the pivot plane of the coupling and thickened boiler feed pump shaft they are running very satisfactorily and have been doing so for over 4 years.

In the boiler feed pumps the critical speeds may be suppressed when a pump is running full of water due to the effect of the water in the close internal clearance. Because of this we have considered it desirable to examine the natural vibration frequency of the overhang as a cantilever from the centre of the adjacent bearing, taking note of the appropriate part of the spacer coupling. Our current specifications for boiler feed pumps require that this natural frequency shall be at least 50% above the running speed and preferably more than double.

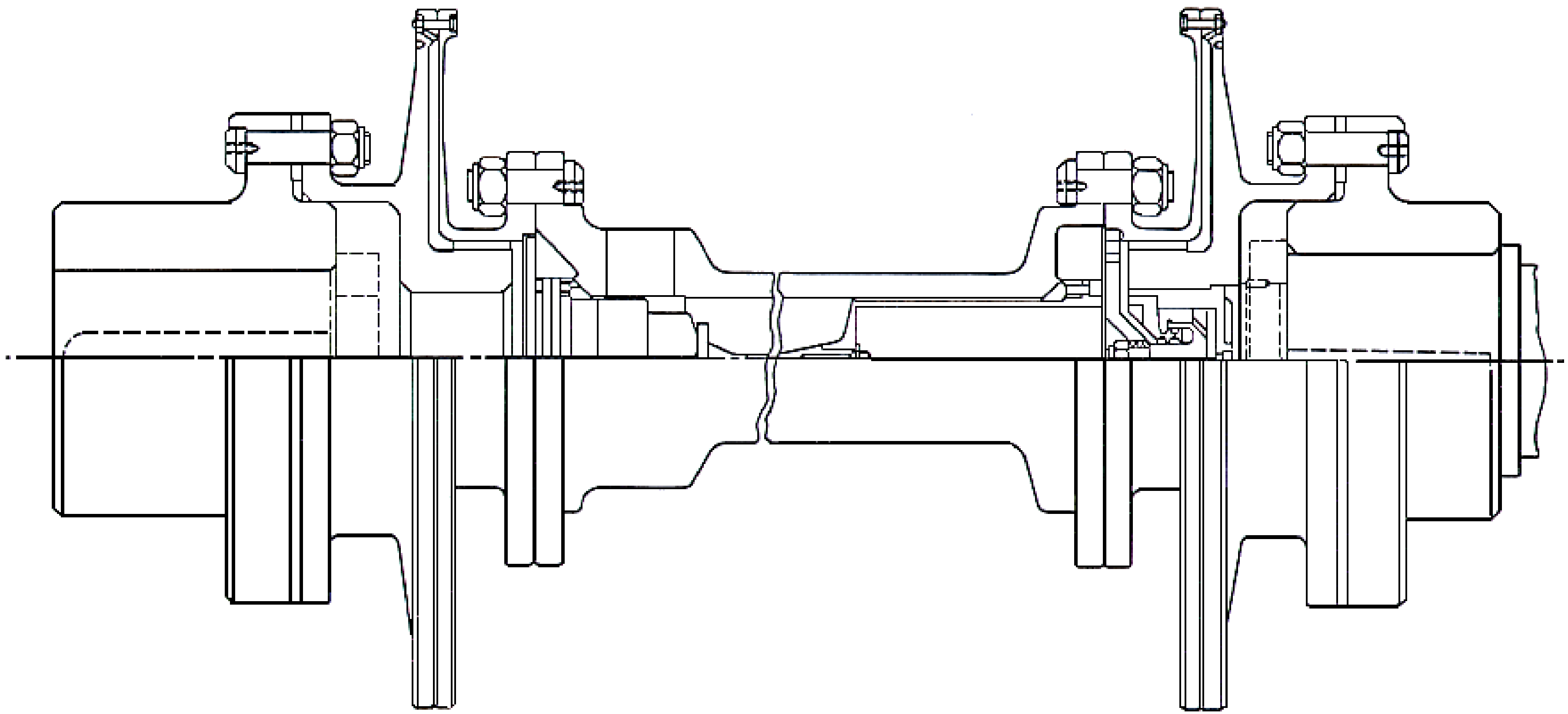

Fig. 7

Typical contoured disc coupling on main boiler feed pump drive

Hinkley Point B

(Shown with torquemeter included)

It is clear that this criterion would be justified with a very stiff shaft between the bearings and a very flimsy overhang. Although it has not been theoretically justified it is nonetheless considered a useful means of assessing shaft overhangs. In practice any flexibility in the main shaft will result in the overhang natural frequency being lower than the cantilever frequency.

The following approximate values were assessed for the overhang frequency of the shafts of these Tilbury 'B' starting / standby pumps at their drive ends.

Original design with long overhang	7,000 cpm
Original pump shaft with short overhang and long spacer double gear coupling	10,000 cpm
Original pump shaft with short overhang and coupling with membrane at pump end and gear coupling at gearbox end	9,000 cpm

It was not assessed for the final design but with the larger shaft is clearly well in excess of 10,000 cpm.

These pump units and couplings were the subject of substantial tests covering both double gear couplings and also a coupling with a membrane unit adjoining the pump. These were reported by Chen (Reference 2) at the 1973 pump conference at Karlsruhe. The tests were extremely useful but the CEGB did not accept his conclusions that the observed phenomena were due to orbiting of the male component of the coupling inside the female component.

The question of the entering of gear type couplings has been considered by Conti-Barbaran (Reference 3). He used the parameter ξ defined as :

$$\xi \qquad \frac{N \quad 10^{15}}{Pn^{3} \quad d^{2}}$$

where N is the load transmitted in HP

n the revolutions per minute

d the pitch diameter of the teeth in mm

P the total weight of the floating parts in kg

His criterion for stable running is that the parameter ξ should be greater than 4 or 5. The long spacer, used in the final version and in the later intermediate versions on these pumps at Tilbury 'B', gives a value of ξ over 20. Accordingly there seems little doubt that the couplings were behaving stably and that the observed vibrations required a different explanation.

In our view the flexibility of the overhang of the pump shaft was the cause with its transverse natural frequency being too close to the running speed; as a result the balance was critical. With the original small shaft the heavier membrane coupling took the natural frequency below the normal running range – 70 – 100% speed. It was predicted that the lighter double gear type coupling would be well clear of the running rage but that with the heavier membrane unit it would still be in the running range. Tests showed that this was the case; accordingly all pumps now have the double gear type coupling and the larger shaft at the drive end and in this form have been running very well for over 4 years.

The lesson that has been learnt from these experiences is that shaft overhangs must be examined in conjunction with coupling selection.

Before final modification the pump units were sensitive and it was necessary to site balance the pumps and couplings. This practice has continued and the Station aim for vibration levels such that the peak to peak bearing amplitude is ± 0.025 mm (0.001 in), which corresponds at a speed of 6721 rpm to an rms velocity of about 6 mm/sec. As far as can be determined these are the only installations of CEGB feed pumps with gear couplings where site balancing may be necessary.

Tilbury 'B' Main Boiler Feed Pumps

The standard main boiler feed pumps at Tilbury 'B' power station originally had a gear coupling connecting them to their driving turbines (Figure 2). (One main feed pump at this station is a different non-standard design). The pumps generally ran satisfactorily with these couplings but there was some small evidence of fretting in the couplings after about 5,000 hours operation; this was explained by the high transverse misalignment which was reported as 1.5 mm for a spacer of 430 mm length. At that time in 1971, there was a reaction against the use of gear couplings in favour of membrane couplings. General experience, as reported in this Paper, shows that the evidence when examined does not indicate that gear couplings were or are unsatisfactory. In many installations they are giving very good service. Unfortunately the space available for a membrane coupling on these pump units was very restrictive. The membrane units were only 100 mm apart and for assembly reasons the bolts on the twp membrane units could not be set in line and were set at 45° so that any misalignment results in a Hooke's joint effect. Further the couplings were 60% heavier than the gear couplings that they replaced. The net result was that the use of the membrane couplings resulted in vibrations. One pump unit has now reverted to the original gear coupling and is running satisfactorily.

The other two are running satisfactorily with membrane couplings, but it is necessary to site balance the units and balancing holes have been provided on the coupling to permit this. This situation must not be taken as a condemnation of membrane couplings. It stresses the need for good detailed engineering of the complete installation. Couplings cannot be considered in isolation.

Fawley Starting/Standby Pumps

As originally constructed the main drive on the starting / standby pumps at the CEGB power station at Fawley was similar to but larger than that of the original design of the starting / standby pumps at Tilbury 'B' shown in the top of Figure 4, with a comparable long rigidly connected overhang, which in this case was about 700 mm. Early operation of these pumps was not fully satisfactory. Changes were made and these are discussed later. At the time no completely satisfactory explanation for the unsatisfactory behaviour was forthcoming, although the overhang natural vibration frequency considered as a cantilever was 7,000 rpm, rather closer to the running speed of 5,588 rpm than desirable. More recent consideration suggests that the explanation may come from the combination of the friction couples, which will exist in any gear coupling, with the long overhang. If the overall misalignment amounts to a parallel offset, the friction couples from the two ends will be additive. The actual values depend on the true effective coefficient of friction in the coupling teeth but an assessment indicates that the combined couples will be resisted by a transverse force at the ends of these pump shafts and gearbox sun wheels of about 7,000 N. With the long overhang of 700 mm this will give a substantial moment at the pump bearing and result in a measurable deflection at the pivot plane of the coupling. This in turn will result in out of balance forces increasing the deflection even further.

The transverse load will be reduced by lengthening the spacer since it is inversely proportional to the length of the spacer. Further shortening the overhang – which will accompany lengthening the spacer – will reduce the deflection at the changed position of the pivot plane by a factor of about 10: this occurs in two ways, firstly by direct reduction of the load and secondly by reducing the length since the deflection varies with the cube of the overhang length. This modification was made; at the same time the gear coupling at the pump end was replaced by a membrane coupling. In this form the pumps have been running very well. General CEGB experience suggests that they would have run equally well if the spacer had been lengthened and the overhang length reduced and a double gear coupling retained.

To have changed to a membrane coupling located at the original pivot position would have been unsatisfactory since a radial force would still have been transmitted through the membrane coupling due to the friction couple at the gear coupling at the remote end of the spacer. It would have only resulted in the transverse load and deflection being halved, whereas moving the pivot plane gives a much greater reduction in the deflection.

Cottam Starting/Standby Boiler Feed Pump

In 1970 a number of failures occurred on the epicyclic gearboxes and adjoining couplings on the starting / standby boiler feed pumps at Cottam power station. While the investigations were not conclusive as the damage was fairly substantial, the evidence suggested that excessive transverse misalignment was a possible cause: in one case it was assessed that the cold transverse misalignment had been 0.99 mm (0.038 in) resulting in damage to both the coupling teeth and sun wheel of the epicyclic gearbox. The arrangement is similar to that of the final arrangement of the Tilbury starting / standby pumps (Figure 3).

Boylan (Reference 1) has shown that a safe maximum sliding velocity in a gear coupling is 125 mm/sec (5 in/sec) based on a number of observations. It is not clear from his paper whether this velocity is influenced by the surface hardness of the coupling teeth. Accepting this value for the Cottam high speed couplings, which run at 6,000 rpm, gives a maximum permissible transverse misalignment of 1.02 mm (0.042 in) at the pump end and 1.45 mm (0.057 in) at the smaller coupling at the gearbox end. The cold transverse misalignment figure was too close to the permissible value at the pump end. Movements in service would be expected. Excessive transverse misalignment could therefore have been the cause of failure of some of these gearboxes and couplings, although this is not conclusive. The permissible inclination is 2.1 in 1,000. The coupling teeth were straight without any crowning or barreling and this is the arrangement on all of the similar installations on our 500 MW units. With such low permissible angular misalignment restricted by the sliding velocities there is little case for any crowning or barreling. Cottam power station decided that crowning and barreling should be added to their coupling teeth and this has been done. Total running hours on the 8 motor driven feed pumps at this station are now 180,000 hours on uncrowned and unbarelled teeth and 70,000 hours with crowning and barreling. Our general experience suggests that the crowning and barreling is unnecessary: equally the Cottam experience suggests that it is not harmful.

The conclusion from this is that angular or transverse misalignment is in many cases the limiting factor on gear type couplings. With reasonable spacer lengths – of the order of 500 – 600 mm – the movements experienced in operation should keep with the permissible misalignments provided initial setting up is good. I only know of one instance on CEGB boiler feed pump installations where permissible misalignment on gear type couplings was restrictive: this was on a gear type coupling at another station transmitting 7600 kW at 8650 rpm. For this the maximum permissible transverse misalignment would have been only 0.24 mm (0.0095 in). It is unreasonable to expect normal movements and transverse expansions on feed pump installations to be kept below such small values although our experience suggests that they can be kept within about 0.5 to 0.7 mm. This coupling showed significant wear after a relatively short period of operation and has been replaced by a membrane coupling. The distance between the rows of gear teeth was only 165 mm. A longer gap would have permitted more transverse misalignment.

Since the permissible sliding velocity is a limiting factor for gear type couplings the CEGB are examining the possibilities of carrying out tests to determine whether a higher value than 125 mm/sec is acceptable with surface hardened teeth.

Rugeley ‘B’ and Cottam Main Boiler Feed Pumps

The designs of the main boiler feed pumps at Rugeley ‘B’ and Cottam power stations are the same but they are driven by different makes of turbine. As originally built they had multi-pack membrane couplings connecting all the various shafts. A coupling failure occurred at Cottam and both stations have suffered failures of the gearboxes between the pressure stage pumps and their boosters. Further, 4 bolt failures have occurred in the membrane couplings of a very similar installation belonging to another Utility.

Examination of the evidence – initially at Rugeley – suggested that there was a torsional problem. Both theoretical and experimental investigations revealed that the fundamental torsional vibration coincided with the booster pump speed near the maximum running speed. Clearly the bolts of membrane couplings are unlikely to withstand the alternating loading arising from torsional fluctuations so failures were inevitable. The investigations have been reported by McCheyne (Reference 4). The remedy applied at Rugeley was to change the low speed couplings between the booster pump and the gearbox to Holset flexible couplings incorporating rubber blocks and to reduce the overhang of both the bearing housing and of the shaft at the booster pump end of the pressure stage pump; the former change removed the fundamental torsional frequency from the booster pump speed while the latter reduced the response to out of balance effects by a factor of 6.

Both Rugeley pumps were modified in this way and have since been running very successfully and have accumulated 17,000 hours of operation. Membrane couplings have been retained in the original positions apart from that where the Holset coupling has been fitted.

CONCLUDING REMARKS

This Paper has reviewed the experiences of the CEGB with flexible couplings on high speed boiler feed pump drives. Three types of coupling – gear, multi-pack membrane and contoured disc – have been used and all three types have had successful use although the experience with the contoured disc type is rather limited. No one type of coupling is absolutely ideal. Gear couplings have limited transverse misalignment capacity, which in most feed pump installations should be acceptable, but they can be designed to accommodate any reasonable axial displacement, they will normally be lighter and can have their pivot planes positioned nearer the shaft bearings.

Membrane couplings have much greater capacity for transverse misalignment although this is reduced if their axial displacement is near the limiting value. Couplings designed primarily on the basis of torque capacity may be limited on permissible axial displacement; this can usually be increased but at the expense of size and weight. In most cases the weight will be greater than for gear couplings and the pivot plane further from the bearings.

The advantages and disadvantages of contoured disc couplings are generally similar to those of the membrane couplings. Figure 8 taken from Reference 5 shows how the weights of the three types of coupling vary with torque capacity.

Finally, I cannot stress too highly the need for couplings to be considered at an early stage of design; their effect on shaft dynamics must be examined for high speed machines. The axial space available must be sufficient to enable the coupling to function satisfactorily. Transverse misalignments and axial expansions must be considered. If this is all done, there should be no problem in fitting couplings that will give fully satisfactory service.

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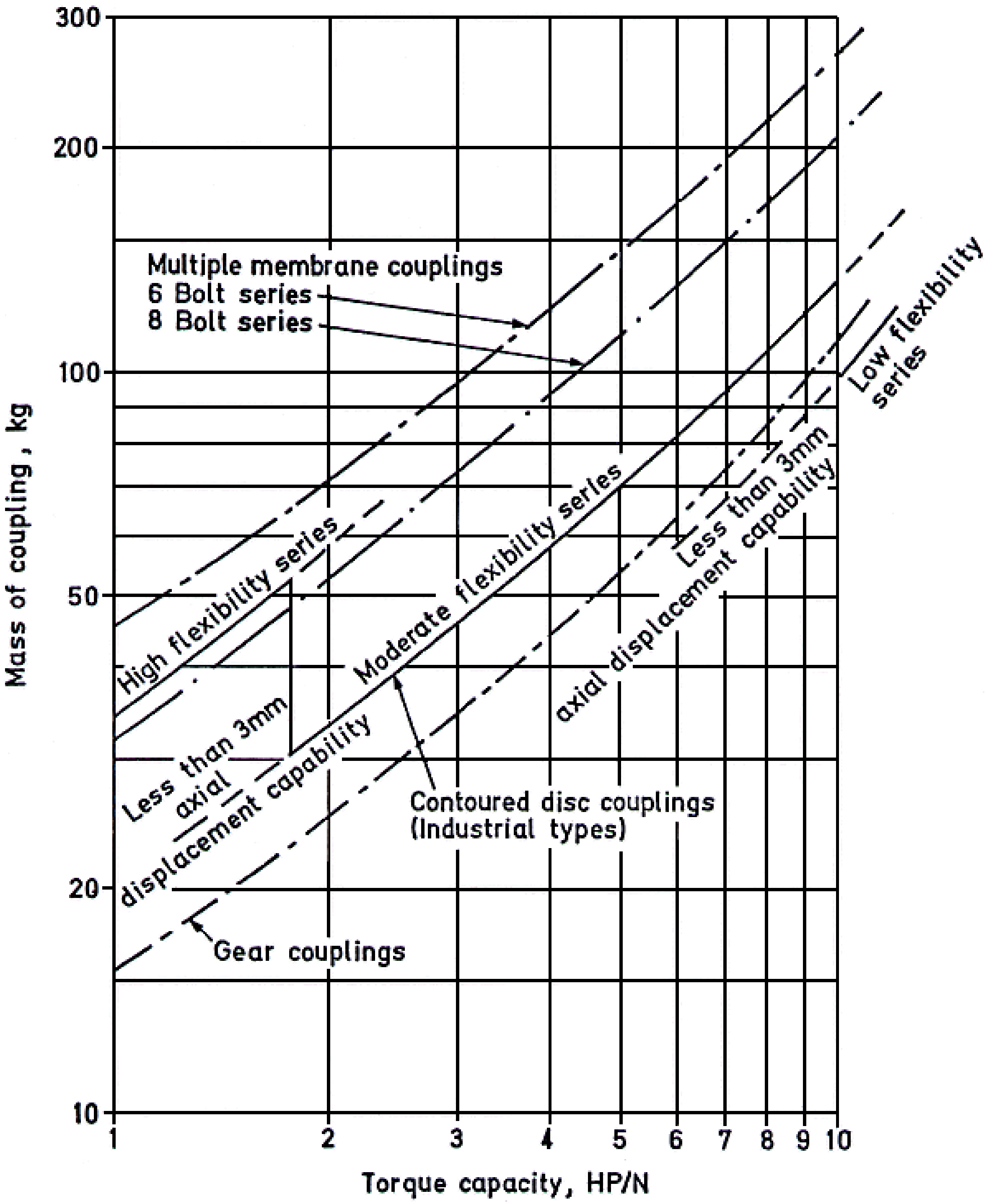

Fig. 8

Masses, excluding hubs for commercial spacer coupling designs

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