



## HYDRAULIC REMOVAL OF KEYED HUBS

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### INTRODUCTION

During the last decade, keyless fits have become the preferred method of mounting High Performance coupling hubs on equipment shafts. There are multiple advantages to this type of connection, the relative ease of hub installation and dismounting is one of them (see Ref. 2).

However, keyed interference fits both straight and tapered, are still being used on a fairly large scale. One of their major drawbacks is the difficulty of removing the coupling hub from the shaft. Virtually all keyed hubs are supplied with means to attach to mechanical pullers, but in a few cases even the use of powerful hydraulic cylinders is not sufficient to remove the hub. It is necessary then to apply heat uniformly around the hub (normally with a torch and rosebud) while the pulling force is maintained. During this time one has to make sure that only the hub expands; the shaft must be shielded from heat and if there is sufficient space in the back of the hub, wet rags or dry ice can be used to lower the shaft temperature. Unfortunately, this method too often results in "cooked" hubs destroyed by overheating, or, severely damaged shafts and bores, not to mention the aggravation and possible physical harm to maintenance workers who must remove the hubs.

Recently, numerous experiments aimed at easing the removal of keyed hubs were conducted in the Kop-Flex research laboratory (see also Ref. 3). The hydraulic injection method described in this paper offers several distinct advantages compared to the traditional removal procedures:

- easy removal is allowed in refineries and chemical plants where safety regulations restrict the use of flame.
- the potential of scoring the bore or the shaft is minimized due to the inherent lubrication of the surfaces in contact.
- maintenance work is simplified; the necessary equipment is inexpensive and readily available.

- the risk of damaging the coupling parts by overheating is eliminated.

### PRINCIPLE OF OPERATION

The hub removal tooling package comprises two pressure systems. Oil is injected between the hub and the shaft through the internal pressure line. The oil pressure causes the hub to expand and a film of oil separates the bore and shaft surfaces. The external pressure system controls a hydraulic cylinder, which exerts the axial force required to remove the hub.

As opposed to the circular oil grooves used in keyless hydraulic designs, the circumferential oil grooves must be crescent shaped to prevent leakage through the keyways. During dismounting, oil does leak from the hub to shaft interface, as designed; however, the hydraulic pressure is large enough to significantly reduce the axial force needed for removal.

### SYSTEM DESIGN FOR TAPER BORED HUBS

A schematic of the removal system is presented in Fig. 1. The injection of oil between the hub and the shaft through the internal pressure line facilitates hub removal in two ways:

- it reduces the friction coefficient between the surfaces in contact, thereby lowering resistance to axial pull.
- in addition to the radial force which expands the hub, an axial component also results, due to the angle of taper; its effect is to push the hub off the shaft.

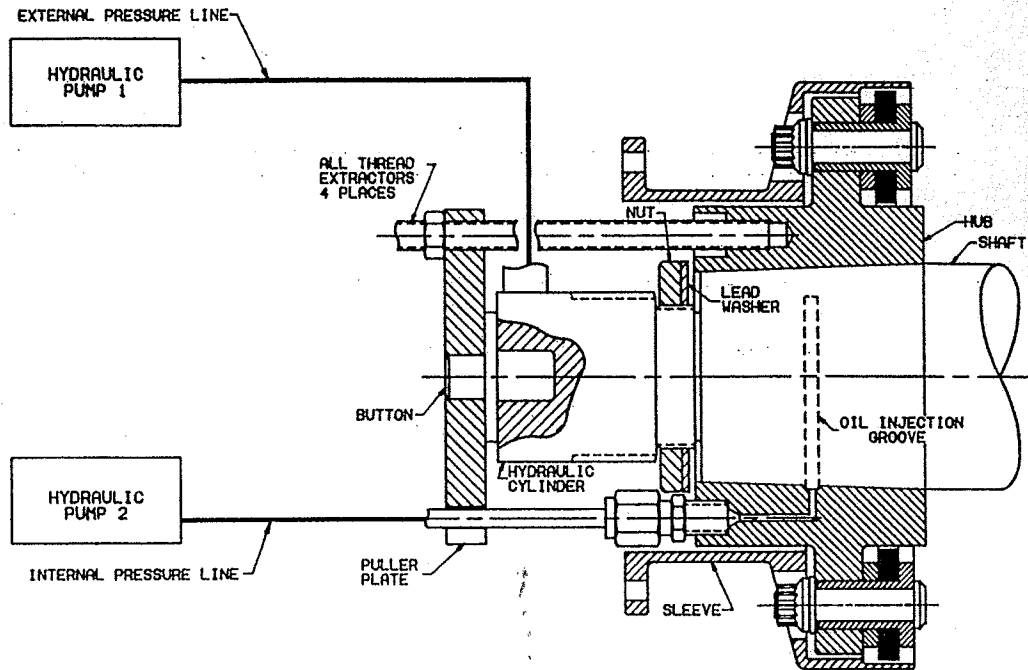


Fig. 1 Hydraulic Removal of Keyed Taper Bored Hubs

Calculation Model

The selection of the hydraulic cylinder, sizing of the threaded extractors, etc., is based largely on determining the external force necessary for removal. The calculation model presented here represents a combination of classic shrink fit equations and empirical coefficients determined experimentally.

The block diagram of the algorithm is presented in Fig. 2.

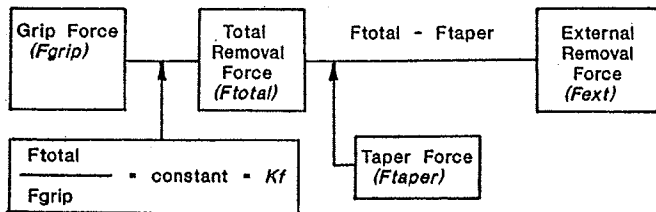


Fig. 2 Calculation Model for the Removal Force

- "Grip Force" represents the axial force needed to overcome the dry friction of the hub against the shaft; it is produced by the initial shrink fit installation of the hub.
- "Total Removal Force" is the force needed for the hydraulic removal of the keyed hub and is expressed as a percentage (determined by experiment) of the initial "Grip Force". It has two components:
- "Taper Force" - an axial component of the oil injected at the bore between the hub and the shaft; it is proportional to the area of the tapered bore, projected in a plane perpendicular to the axis of the shaft.

- "External Removal Force" - the remainder of the "Total Removal Force", to be applied by the hydraulic cylinder.

The complete definition of terms and the equations are presented in the Appendix. For simplicity, the presence of the keyways was neglected in calculations; it was assumed that experimental coefficients (i.e.  $K_f$  in Fig. 2) would account for this approximation.

The relative magnitude of the removal forces is illustrated in Fig. 3.

The numerical values, representing averages of actual test results, indicate that the external removal force applied by the hydraulic cylinder is only 13-25% of the grip force. In other words, the force needed for hub removal with hydraulic assistance is 4 to 8 times less than the force without hydraulic assistance.

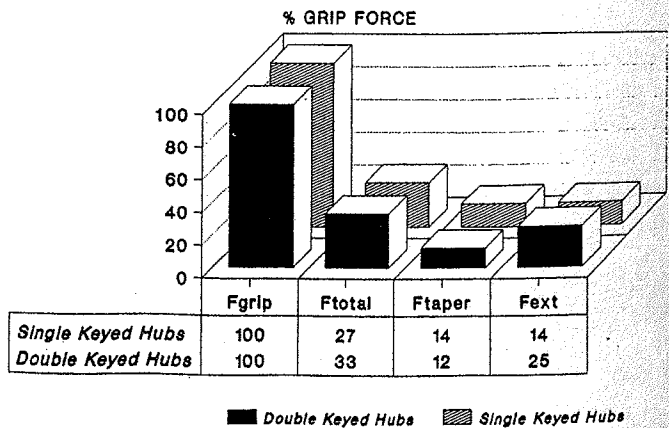


Fig. 3 Axial Forces in the Hub Removal System

## Bore Pressure and Hydraulic Pressure

The governing parameter in the design of the hydraulic removal tooling package is the pressure at the hub/shaft interface. When the hub is initially installed on the shaft with an interference fit, a certain amount of pressure is developed between the mating surfaces. We shall identify this variable as bore pressure.

It is important to realize that the pressure generated in the internal pressure line leading to the hub bore is independent of the shaft size. This means that the same internal hydraulic system used for a 2" diameter shaft can also be used for a 6" diameter shaft. The external hydraulic system however is size dependent. While the pump and fittings can be used for different shaft diameters, the hydraulic cylinder force requirement is directly related to the shaft size: the removal force is higher for larger diameter shafts.

Returning to the subject of bore pressure (BP), its mathematical expression can be written to contain two non-dimensional variables:

$$BP = \frac{i E}{2} \frac{R^2 - 1}{R^2} \quad (\text{Equation 7 in the Appendix})$$

where:

- i = interference rate (diametral interference/shaft diameter)
- R = hub body/bore ratio

The dimensional parameter E (modulus of elasticity) is expressed in the same units as the bore pressure. For steel hubs (E = 30,000,000 psi) and for the most common R value of 1.5, the previous equation becomes:

$$BP = i \cdot 8.33 \cdot 10^6 \quad (\text{psi})$$

Since the mathematical expression of the bore pressure does not contain terms related to hub dimensions (diameter, length, etc.), it is apparent that for a given interference rate and hub body/bore ratio, the bore pressure is the same for any shaft diameter.

In general, keyed fits are designed with interference rates of less than .001 in/in; the most common values are .0005 and .00075 in/in. For this analysis, a conservative approach is to adopt an interference rate of .001 in/in which relates to a bore pressure of 8,330 psi.

It is clear that if the pressure of the oil in the internal hydraulic system reached 8300 psi and were reasonably uniform around the circumference of the bore, the hub would come off by itself, due to the "taper" force which tries to push it off the shaft. The expansion of the hub is not uniform however, due to the presence of keyway(s) and segmentation of the injection grooves. For this reason, the internal hydraulic pressure cannot reach the level of the bore pressure and the oil will leak at the ends of the hub. For calculations, the "leakage" pressure is taken as a fixed ratio (K<sub>p</sub>) of the bore pressure, determined experimentally for single-keyed and double-keyed configurations:

- single-keyed: K<sub>p</sub> = .69
- double-keyed: K<sub>p</sub> = .57

The practical significance of these numerical values is that for the same interference rate, the oil will leak at a lower pressure for the double-keyed hub. Intuitively this can be explained by considering the hub shape for the two cases.

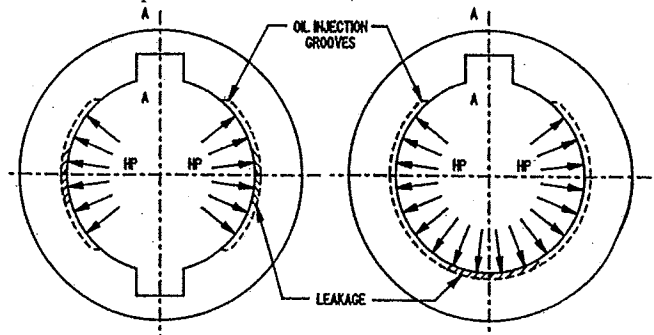


Fig. 4 Internal Hydraulic Pressure (HP) Distribution in Double and Single Keyed Hubs

The double-keyed configuration is "balanced" about the vertical axis. The oil injected under pressure, acting on the left and right hub sections, is resolved in internal forces which tend to separate the hub from the shaft. The presence of the keyways is diminishing the hub resistance to internal pressure (radial stiffness) and oil leakage will take place in the marked areas.

The single-keyed hub lends itself to a more uniform oil distribution. In a sense, the pressure acting opposite the keyway "fights" the hub tendency to stretch in the A-A section. The hub separation from the shaft, and therefore leakage, will take place at a slightly higher internal pressure value, compared with the double-keyed hub.

During the actual hub removal procedure, leakage is unavoidable, but the flow of oil is very small compared with the capacity of the pump and the loss does not create problems. With a rapid pumping motion, the internal oil pressure can be maintained at a level exceeding the leakage pressure, thereby facilitating removal.

## Removal Forces: Test Results and Design Considerations

The summary of external removal forces for the tested hubs, as well as the theoretical values recommended for design and selection of the hydraulic cylinder are presented in Fig. 5.

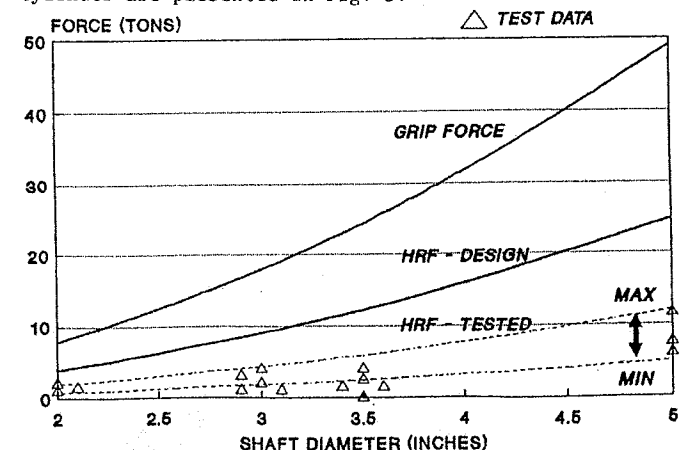


Fig. 5 Grip Force and Hydraulic Removal Forces for Taper Bored Keyed Hubs

Given a certain shaft size, aside from the interference rate, there are several parameters which affect the magnitude of the hydraulic removal forces, such as:

- angle of taper (1/2 in/ft, 3/4 in/ft, etc.)
- single/double keyed
- removal technique

The "taper" force, which is proportional to the projected area of the bore, will be higher for steeper angles of taper (3/4 in/ft or more) than for shallow ones. This has a direct effect on the external removal force: a lower force will be required for the steeper angles (see Fig. 2).

It has been shown in the previous section that the leakage pressures are different for the single- and double-keyed configuration. As a result, for the same taper, the single-keyed hub which relates to a higher leak pressure, will generate a larger taper force, thereby reducing the external force requirement. In short, the single-keyed, 3/4 in/ft tapered hub and the double-keyed, 1/2 in/ft tapered hub will be associated with the lowest and highest external forces, respectively, of all four possible combinations (see chart in Fig. 3).

The experience of the operator also has an effect on the amount of external force needed. As noted from the review of the removal procedures (see Appendix B), at a certain point during this operation, both the internal and external pressure systems need to be actuated simultaneously. If the pumping motion in the internal system is rapid, the pressure build-up will exceed the leakage pressure. As a result, a lower external removal force will be needed. During several experiments conducted with a single-keyed, 3/4 in/ft taper combination, it was even possible to remove the hub without applying any external axial force; the hub "popped" loose due to the internal taper force only.

All these factors explain why the test removal forces in Fig. 5 are situated in a wide band, rather than on a single curve. For actual design, it would be impractical to select the hydraulic cylinder for a particular combination of interference rates, number of keys or angle of taper. It is recommended that only the maximum external force requirement be considered, and that the capacity of the cylinder exceed the force value mentioned above by a good safety margin. For example, in Fig. 5, the removal force is based on an interference rate of .001 in/in and on a safety factor of 2, applied to the maximum calculated external force. Since in reality the interference rate is in the .0005 in/in-.00075 in/in range, the combined safety factor will be even higher (2.7-3). We feel this would be sufficient to account for unforeseen problems: excessive draw, badly damaged contact surfaces, or inexperienced operators.

In the selection of hydraulic components, cost savings will result if the system is based on low pressure hoses, fittings, pump and gages (10,000 psi maximum). The high pressure components, (20-40,000 psi) normally used for the removal of keyless hubs, are much more expensive. As explained in the previous section, bore pressures in keyed fits will not exceed 8300 psi (internal system). For the external system, a wide range of hydraulic cylinders are commercially available, generating forces from 5 to 150 tons at the rated pressure of 10,000 psi.

#### Other Design Recommendations

- a) The width of the crescent-shaped injection groove does not significantly affect the hub removal force. For practical considerations, it can be set between 1/8 in. and 3/16 in. across a diameter shaft range of 2 in. to 5 in.
- b) For single-keyed hubs the groove should cover approximately 270° of the bore circumference, while for double-keyed hubs, the two segments span an arc of 90°- 100° each.
- c) Insertion of a soft lead or copper washer between the hub face and the nut (Fig. 1) will prevent hub damage by cushioning the impact created when the hub to shaft connection is broken loose.
- d) The quality of the bore surface is not crucial for optimum performance. A standard 125 RMS finish is perfectly acceptable.
- e) The single-keyed hub machined for hydraulic removal is inherently unbalanced. In order to avoid extensive drilling at the final balance operation, it is recommended that provisions for corrections be made by design, i.e. counterbores around the puller holes, opposite the oil injection zone.

#### Safety Recommendations

- 1) Do not attempt hub removal without the retainer nut in place.
- 2) Do not stand in front of the shaft during hub removal.

#### SYSTEM DESIGN FOR STRAIGHT BORED HUBS

While the principle of operation is the same as for taper bored hubs there is one significant difference which affects the components of the system and the hub modifications for hydraulic removal: the axial force exerted by the cylinder needs to be applied over the entire hub/shaft engagement distance. For taper bored hubs, the "pull" distance is roughly equal to the draw.

A schematic of the removal system is presented in Fig. 6.

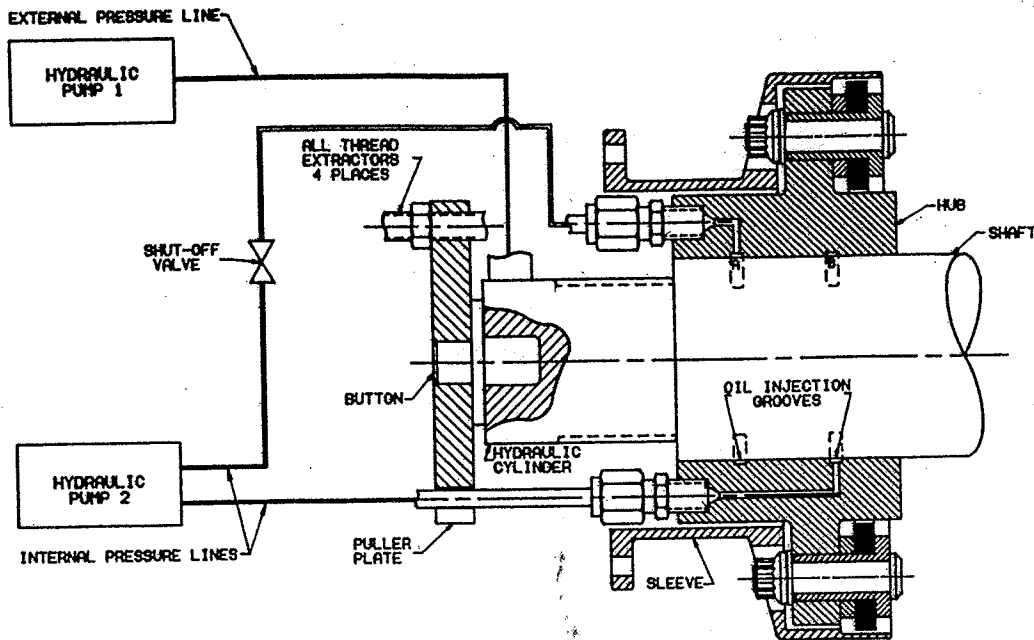


Fig. 6 Hydraulic Removal of Keyed Straight Bored Hubs

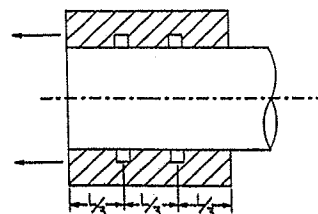
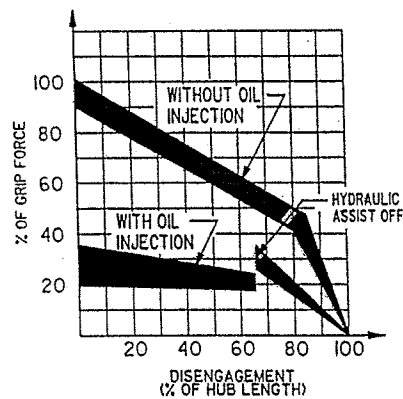
The total force needed for hydraulic removal is also relatively low: 20-35% of the removal force without hydraulic assist (see Fig. 3). The "pull" capacity of the cylinder however, must be higher than for the same size taper-bored hub because the taper force component is absent for straight shafts; the entire force needed for removal must be exerted by the hydraulic cylinder alone.

A single oil injection groove is not sufficient due to the longer pull distance. Several configurations were investigated; the one that performed best consisted of two crescent shaped grooves, each placed at equal distances (one third of the hub length) from the hub ends.

Fig. 7 illustrates the variation of the removal forces for straight shafts, with and without hydraulics, as a function of the hub/shaft disengagement distance.

It should be noted that hub removal is assisted by pressurized oil only for the first two thirds of disengagement length. When the second groove overhangs the shaft end, the internal pressure lines are disconnected. For the last removal step, the hydraulic cylinder acts alone, unassisted by oil under pressure. At that point, the hub to shaft engagement distance - which is directly proportional to the "grip force" - is limited, and the surfaces in contact are well lubricated. Both these factors lead to relatively low removal forces required from the hydraulic cylinder. The removal sequence is described in Appendix B.

The double-keyed straight-bored configuration is perhaps the most complicated of all the possible combinations because the two injection grooves need to be segmented into four small grooves, to clear both keyways. This requires more extensive hub machining and several additional hydraulic system components, but the dismantling procedure works just as well as for the other configurations.



- EXAMPLES:
- A) 3 INCH DIA SHAFT, 1 KEY  
 GRIP FORCE = 16 TONS  
 HYDRAULIC REMOVAL FORCE = 3.5 TONS  
 L = 3 INCH
  - B) 3.5 INCH DIA SHAFT, 2 KEYS  
 GRIP FORCE = 25 TONS  
 HYDRAULIC REMOVAL FORCE = 8 TONS  
 L = 4 INCH

Fig. 7 Typical Removal Forces for Straight Bored Hubs

## REFERENCES

- 1) Timoshenko. S., Strength of Materials, 3rd Edition, p. 212, (Van Nostrand, 1958).
- 2) Michael M. Calistrat, Hydraulically Fitted Hubs, Theory and Practice, Paper presented at the Ninth Turbomachinery Symposium, (Houston, 1980).
- 3) Michael M. Calistrat, Flexible Coupling Installation (Figure 58), Paper presented at the National Conference on Power Transmission (Nov. 1981 - Chicago).

## APPENDIX A: VARIABLES AND CALCULATIONS

### Nomenclature:

A = Bore area	(sq. in)
A <sub>T</sub> = Area of the axial projection	(sq. in)
BP = Bore pressure	(psi)
d = Small bore diameter	(in)
D = Large bore diameter	(in)
D <sub>H</sub> = Hub body diameter	(in)
E = Modulus of elasticity	(psi)
F <sub>GRIP</sub> = Grip force: axial force needed to remove the hub without hydraulics	(lb)
F <sub>EXT</sub> = Removal force produced by the hydraulic cylinder	(lb)
F <sub>TAPER</sub> = Taper force: axial force produced by the internal pressure on the projected area of the taper bore	(lb)
F <sub>TOTAL</sub> = Total axial force to remove the hub with the hydraulic system	(lb)
HP = Internal hydraulic pressure	(psi)
i = Interference rate: diametral interference / bore dia.	(-)
I = Diametral interference	(in)
K <sub>F</sub> = Constant: F <sub>TOTAL</sub> /F <sub>GRIP</sub>	(-)
K <sub>P</sub> = Constant: Bore pressure/internal hydraulic pressure	(-)
L = Bore length	(in)
μ = Apparent coefficient of dry friction between the hub and shaft surfaces	(-)
R = Hub body diameter/bore diameter	(-)
T <sub>G</sub> = Constant: F <sub>TOTAL</sub> /F <sub>GRIP</sub>	(-)

### Calculation Model

Refer to Figure 2

- 1) Determine Grip Force

The general equations are:

$$F_{GRIP} = BP \cdot A \cdot \mu \quad (1)$$

$$BP = \frac{I \cdot E \cdot (D_H^2 - D^2)}{2 \cdot D \cdot D_H^2} \quad (\text{Ref. 1}) \quad (2)$$

$$A = \pi \cdot d \cdot L \quad (3)$$

$$\mu = 0.15 \text{ (determined experimentally)} \quad (4)$$

The grip force can be determined by substituting (2), (3) and (4) in (1).

Note: The bore pressure can be expressed in terms of the non-dimensional parameters "i" and "R" as follows:

$$i = \frac{I}{D} \quad (5)$$

$$R = \frac{D_H}{D} \quad (6)$$

Substituting (5) and (6) in (2), the equation becomes:

$$BP = \frac{i \cdot E}{2} \cdot \frac{R^2 - 1}{R^2} \quad (7)$$

- 2) Determine Total Removal Force:

$$F_{TOTAL} = F_{GRIP} \cdot K_F \quad (8)$$

The values of the constant K<sub>F</sub>, determined experimentally are:

$$K_F = 0.27 \text{ for single-keyed hubs}$$

$$K_F = 0.33 \text{ for double-keyed hubs}$$

- 3) Determine Taper Force

The general equations are:

$$F_{TAPER} = HP \cdot A_T \quad (9)$$

$$HP = BP \cdot K_P \quad (10)$$

The values of the constant K<sub>P</sub>, determined experimentally are:

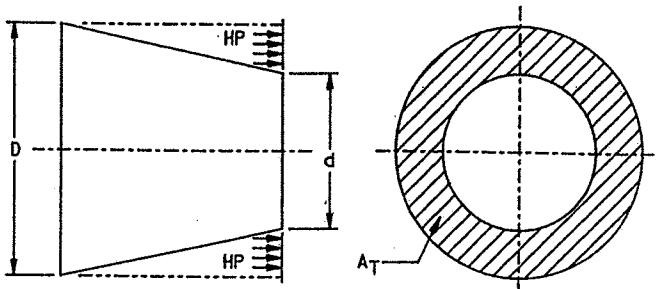
$$K_P = 0.69 \text{ for single-keyed hubs}$$

$$K_P = 0.57 \text{ for double-keyed hubs}$$

The area of the axial taper bore projection is:

$$A_T = \frac{\pi (D^2 - d^2)}{4} \quad (11)$$

(Keyways are neglected)



The taper force can be determined by substituting (10) and (11) in (9).

- 4) Determine External Removal Force

$$F_{EXT} = F_{TOTAL} - F_{TAPER} \quad (12)$$

#### APPENDIX B: HYDRAULIC REMOVAL PROCEDURES FOR KEYED HUBS

##### B1 - Taper Bored Hubs

Refer to Fig. 1.

- 1) Remove original shaft nut.
- 2) Install lead washer and the special nut provided with the hub removal package. The gap between the lead washer and the face of the hub must be slightly larger than the initial draw.
- 3) Install hydraulic fittings in the hub and connect to hose(s) or tubing leading to pump #2.
- 4) Place the hydraulic cylinder on the end of the shaft and install puller plate over the centering button. Connect the cylinder to pump #1.
- 5) Install the threaded extractors.
- 6) Tighten the extractor nuts snugly, making sure the cylinder is centered and seats flat on the shaft end.
- 7) Activate hydraulic pump #2 to build up pressure in the internal pressure line(s), until oil starts leaking at either end of the hub.
- 8) While maintaining maximum internal pressure with a quick pumping action, activate pump #1 connected to the hydraulic cylinder until the hub is released. (A distinctive "popping" noise will be heard as the hub hits the lead washer).

##### B2 - Straight Bored Hubs

Refer to Fig. 6.

- 1) Identify and match the oil injection grooves with the corresponding internal pressure lines: the NPT holes in the face of the hub leading to the "A" and "B" injection grooves are marked accordingly.
- 2) Install hydraulic fittings in the hub and connect the hoses to pump #2, as shown. The shut-off valve should be on the pressure line leading to groove "A".
- 3) Place the hydraulic cylinder on the shaft end and install puller plate over the button. Connect the cylinder to pump #1.
- 4) Install the all-thread extractors as shown.
- 5) With the shut-off valve in the "open" position, activate pump #2 until oil starts leaking at either end of the hub.
- 6) While maintaining maximum internal pressure (quick pumping action for pump #2), activate pump #1 connected to the hydraulic cylinder until the hub starts moving. This will take place in steps ("stick-slip" type motion), punctuated by a characteristic noise.
- 7) When the hub disengagement approaches the stroke limit of the piston, the nuts should be retightened on the threaded extractors after releasing pressure in the cylinder.
- 8) As the first groove ("A") is about to overhang the end of the shaft, the shut-off valve must be closed. Continue hub removal while injecting oil through the second groove "B" only.
- 9) As groove "B" approaches the end of the shaft, stop actuation of pump #2. Continue hub removal for the last third of engagement by pressurizing the hydraulic cylinder only.