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ADVANTAGES OF THE HYDRAULIC TIGHTENING OF THREADED CONNECTIONS IN RECIPROCATING COMPRESSORS.

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Adequate and very precise preloading can be effected in threaded connections of large diameter by using hydraulic tightening. This system is widely used on reciprocating compressors, mainly to increase reliability and facilitate maintenance.

INTRODUCTION

Threaded connections, widely used in the mechanical industry are often critical, due to the geometry notching, especially when subjected to cyclically varying loads and consequently to fatigue stresses.

They are utilized to ensure that two or more parts of a machine, under the operating loads, remain in contact with a residual force capable to ensure the functions for which they are designed (movement of components, gas seal, etc.).

Obviously, this depends on the operating loads and on the force resulting from the initial tightening (preloading), which is given by the product of the thread root area times the stress generated on this area by the action of tightening the connection.

While these are elementary concepts of machine design, it should be noted that design engineers are often concerned with only one of the two factors of this product, the thread root area, i.e., the size of the screw thread. The other factor, the tightening stress, is often neglected, as if this procedure automatically should result in the value desired by the designer, who will then be ready to tell you, in the unlucky event of failure, that this was caused by insufficient tightening. And it is highly probable that this explanation is true, especially in the case of a thread of large size. When in fact the connection is sufficiently preloaded, the thread is subjected to only a part of the external load and thus to its fluctuation as fatigue stress. When instead there is no preloading, all of the external load is discharged onto the tie-rod, decisively increasing the stress level, at times enough to result in fatigue failure.

Undoubtedly, tightening a screw thread with diameter of 70 mm or larger size is not an easy matter, especially when accessibility is poor.

For experimental purposes, a threaded connection with screw thread 90 mm. in diameter was arranged at ground level in an easily accessible position. The system was instrumented with strain gauges for exact measurement of the preloading generated by tightening. A skilled worker was instructed to tighten the connection as far as possible with a wrench and hammer. The result was that the worker considered tightening to be complete when the stress on the thread root area was approximately 70 N/mm².

Subsequent the worker was instructed to continue tightening the connection to obtain higher values. In spite of the fact that the worker was convinced that this procedure would damage the connection, it was impossible to exceed the value of 105 N/mm², which is less than half of the value predicted by the design engineer, i.e., 220 N/mm², and less than a fifth of the capacity of the material normally utilized for major connections, which has a yield point of 600-900 N/mm².

On the basis of these simple considerations, it is obvious that the tightening of major mechanical components, especially

those of large size, cannot be left to the discretion of the worker.

This aspect is normally underestimated also in the standards and specifications imposed by customers on machine manufacturers. On the one hand, preloading of 1.5-2 times the operating load is required; on the other hand, very often neither tightening procedures nor the configuration of the connection are specified, ignoring the fact that, if these are not appropriate, it will be possible to obtain preloading only slightly higher or even lower than the stress levels allowed by these same standards for the connection in question when it is subjected to operating load.

As is well known, there are various systems for obtaining a "controlled tightening" value.

Basically, these can be divided into three groups:

- tightening by controlled torque;
- tightening by torque with measurement of elongation of part subjected to tensile load;
- tightening by controlled pure axial expansion, without twisting of the part subjected to traction.

Included in the first group are torque wrenches and pneumatically or hydraulically actuated wrenches. Both of these present an uncertainty factor, deriving from friction, which may be as much as 40-60%; moreover, torque wrenches are not practically applicable for threads larger than 70 mm in size.

In the second group it is difficult to determine by calculation the deformation of the tightened element as well as, especially for connections with short tie-rods, the accuracy of the measurement, since the values involved consist of a few hundredths of a millimeter. In this case there are also mechanical difficulties in the tightening procedure itself, for screw threads of large size.

In the third group, the tie-rod is elongated either by thermal means (electric resistance) or mechanical means (hydraulic jack) without the application of torque. The hydraulic jack procedure clearly presents significant advantages, insofar as it generates a very precisely determined preloading (equivalent to the cross section area of the jack piston times the pressure exerted by the tightening pump), does not require measuring to verify the tightening effected, and has no size limitations.

HYDRAULIC TIGHTENING: PRINCIPLES AND FEATURES

WHAT IT IS

A typical hydraulic jack mounted on the end of a tie-rod is shown in Fig. 2. The inside of the jack is screwed directly onto the tie-rod. The outside pushes against a spacer within which the nut is located. Oil is injected into the jack until the pressure read on the pump manometer, corresponding to the desired preloading value, is reached. In this way a tensile force is applied to the tie-rod, which lengthens while the other parts of the connection, compressed by the spacer, shorten.

The nut can be brought into contact with the surface on which it is to rest, simply by rotating it with a small rod passed through special slots on the spacer.

At this point it is sufficient to eliminate the oil pressure and disassemble the jack and spacer; the tie-rod will remain preloaded.

To loosen the connection, the procedure is carried out in reverse order.

WHEN IT IS APPLICABLE

The virtually exclusive characteristic of hydraulic tightening is that great force, practically unobtainable with other systems, can be easily applied to the tie-rod, and disassembly can be carried out with the same ease.

Consequently, this method becomes indispensable when screw threads are large in size. In tightening with a hammer or with a manual torque wrench, in fact, it is possible to obtain only limited torques and thus specific loads that are the lower the larger is the screw size.

WHERE IT IS USED AND WHY

The presumed condition for utilization of hydraulic tightening is generally the need to achieve adequate preloading of large screw threads. There are however other good reasons which can justify its use where:

- reliability and precision of preloading are required. For example when, relying on the elastic operation of the system, we wish to maximize its performance.
- conditions of narrow space and poor accessibility to the connection for manual tightening procedures are existing.
- to obtain even load distribution, simultaneous tightening is necessary of two or more tie-rods. In this case the jacks are fed at the same time by a single pump.
- it is necessary to tighten a threaded coupling made of two similar materials that tend to stick during tightening (for ex., screw and nut thread made of stainless steel). Hydraulic tightening eliminates seizure by avoiding relative motion under load between the threads of the screw and of the nut.
- it is required the use of special geometries for the connection, which otherwise could not be tightened: interposition of calibrated spacers to be inserted during preloading to realize interface instead of acting on the threads.
- it is considered necessary, for reasons of repeatability and precision, to eliminate the uncertainty of friction on the value of the preloading.
- in all the systems that obtain preloading by applying torque to one of the elements of the connection, the assembly tension really obtained depends on the coefficient of friction between the surfaces in relative motion under load during tightening, and thus depends on the condition of the surfaces, which of course is not always the same.

ADVANTAGES FOR RELIABILITY AND MAINTENANCE

In addition to the above-mentioned characteristics, hydraulic tightening offers the following direct or indirect advantages:

- with the same amount of preloading required, it permits utilization of smaller tie-rods, resulting in more compact overall dimensions. With hydraulic tightening in fact, it is possible to obtain very high preloading tensions and thus to utilize the material to have the best advantage.
- For the same reason, the performance of a connection can be enormously improved in terms of supportable load.

- Neither torsion nor flexure is induced during tightening; thus with the same preloading value, the tie-rod is subjected to a lower stress. Or vice versa, higher preloading values can be obtained for a given geometry of connection.
- Safety for operators is increased.
- Maintenance costs are decreased, since maintenance procedures are easier, faster and safer, and the need to intervene for retightening or for accidental causes is drastically reduced.
- Better repeatability of tightening.
For instance, the value of a tightening effected by hammer, often used for large-size screw threads, depends to a high degree on the sensitivity, capability and strength of the worker as well as on the surface conditions of the thread.
- In addition to a minimum of interference, by achieving adequate preloading, it provides a better guarantee against loosening than that of any system of locking between screw and nut thread.

RELAXATION PHENOMENON

Relaxation is the difference between the force applied by the jack to the tie-rod and the residual force with which the tie-rod remains stretched after the nut has been positioned and after the oil pressure has been removed.

There may also be a further reduction in preloading due to settling that takes place during operation.

Relaxation is caused by:

- compression of previously non-loaded zones.
The parts compressed by the jack and the spacer during the tightening stage, while oil pressure is present, are different from those compressed by the nut. Furthermore, the zone compressed by the jack is in general more extensive and thus stiffer than the one compressed directly by the nut.
- Flexure of the threads of the nut and of the tie-rod under load.
- Plastic deformation of the machining crests on surfaces not subjected to load, through the load exerted by the jack.
For example, the flat surfaces between nut and contact surface and the surfaces of the previously unloaded screw thread.

While these causes cannot be entirely eliminated, their effects can be reduced through suitable techniques of engineering, manufacturing and assembly, as for example:

- increasing the stiffness ratio between compressed and stretched parts and trying to reduce to a minimum the difference between the zones compressed in operation and during tightening;
- utilizing surface finishes that render negligible the effect of plastic deformation of the machining crests, during the first assembly.

If the coupling and the tightening equipment are correctly sized, well built and carefully assembled, relaxation is minor in amount and is a characteristic of the geometry of the coupling, the materials of the components and the tightening system (spacer, jack etc.).

Measurements made on the rod/crosshead hydraulic connections system for reciprocating compressor (Fig. 7) have been made for the purpose of optimizing the geometry of the components and precisely evaluating the extent of relaxation and the overall stiffness coefficients of the elements involved, which can be calculated only approximately. In addition to providing direct measurement of the most significant stresses, such experimental

measurements are highly useful for refining calculation methods for systems geometrically similar to those tested.

TYPICAL APPLICATIONS ON RECIPROCATING COMPRESSORS

Hydraulic tightening has been used since 1969 on Nuovo Pignone machines and is standard procedure for the most critical threads of the machine, essentially when called for by the size of the thread, the amount of preloading and the degree of operating safety required. (Figs. 6, 8).

One of the most interesting and significant examples is that of the system of connection between rod and crosshead, which merits detailed analysis. (Fig. 3,4).

In this case, hydraulic tightening has made possible a configuration of the elastic system which is such as to allow substantial increments in the safety coefficient as compared to that of a conventional connection.

The critical points of a conventional connection are sections A, B and C of the rod (Fig. 4). The ratio between these three sections may vary in relation to the shape of the nuts, the type of screw thread, the material and the stiffness ratio between the stretched and compressed parts which determines variation in the stress on the core of the screw $\Delta\sigma$ in sections B and C, for a given external load.

Specifically, by using tensile nuts (the name derives from the fact that the first engaged part of the nut is stretched, Fig. 2) in place of normal ones, it is possible to almost double the fatigue strength of a connection.

The point which is unvarying and is in any case limiting for the performance of the connection shown in Fig. 4 is the external thread (Sect. A), which is exposed to all the load variations transmitted by the piston through the rod. Also acting on this area are the flexural effects, which are added to the main tensile/compression load.

With the hydraulic connection (Fig. 3) the screw thread, which continues to be the most critical point is not directly exposed to the external load but is only partially affected by it. Furthermore, it is not influenced by flexural effects acting on the rod. In comparison to the conventional solution, the reduction in load on the screw thread is sufficient to allow, in spite of the significant reduction in the thread root area, reductions in $\Delta\sigma$ of 2.5-3 times, with the same external load and rod diameter, in comparison to those which would exist in Sect. A of the solution shown in Fig. 4. Such low $\Delta\sigma$ are due to the particular position of the thread within the elastic system, to its configuration and to the favorable ratio between the stiffness of the stretched and compressed parts which act in parallel (see Appendix).

If the inside nut in the solution with hydraulic connection (marked D in Fig. 3) is a tensile nut and is appropriately designed, the maximum permissible fluctuation in stress on the thread root ($\Delta\sigma_{(m)}$) in the two sections (Sect. S Fig. 3 and Sect. A Fig. 4) has approximately the same value. In this condition, all aspects being taken into consideration, it may be estimated that the configuration with hydraulic tightening could withstand a cyclic load at least the double in comparison to the conventional solution, the diameter of the rod being the same in both cases.

The other limitation for performance of the connection consists of the extent of preloading, which must be such the monolithic system remains within a certain safety margin in all operating conditions, and which must ensure that specific loads always remain below the yield point for the materials during both tightening and operation. This and the contrasting need to minimize the $\Delta\sigma$ on the screw thread, by elasticizing the preloaded part of the rod, are the basic factors that determine the

diameters of the tapered stem and of the thread, in the solution with hydraulic tightening, for a given rod diameter.

It may thus be concluded that in the conventional system, since the fatigue strength of a thread ($\Delta\sigma_{lm}$) varies only slightly with increasingly higher mechanical characteristics, the performance of the coupling cannot be appreciably improved simply by using better steels; while the hydraulic connection system makes it possible to exploit the high yield point of the rod material to raise the performance limit of the connection.

The advantage of being able to reduce the diameter of the rod while maintaining the same performance level has significant benefits on the other components of the machine too, namely:

- Thrust reversal on the crosshead pin is improved (a problem that is particularly important when using cylinders for high pressures), and in some cases the need for a tail rod is eliminated.
- Especially on dry machines, rods of large diameter can create significant problems for the general architecture of the cylinders, due to the length of the rider rings and of the piston.
- Since the weight to be supported is lower, the length of the rider rings can be reduced; these spare parts (subjects to wear) are very expensive to replace, particularly in dry machines.
- The alternating masses are reduced, both directly and for the reasons given above, with favorable effects on the dynamic loads and on the forces on the crank mechanisms.

In reciprocating compressors, the introduction of this system of hydraulic tightening has been utilized above all to the advantage of reliability; only in part has it been used to upgrade the performance of the machine.

CONCLUSION

Hydraulic tightening provides significant advantages for the users of the machine.

The operating restraints for tightening can be reduced to a minimum, especially those linked to the amount of preloading; the reliability and performance of connections can be improved, and dimensions and weights can be reduced. Furthermore, if all the advantages and opportunities provided are systematically and rationally utilized up through final formulation of the design, the adoption of hydraulic tightening results in machines that are more compact, lighter and often less expensive.

Furthermore the customers benefits of higher coefficients of utilization of plants deriving from lower maintenance costs and greater safety for personnel.

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APPENDIX

ELASTIC BEHAVIOUR OF THREADED CONNECTIONS

The idealization of Fig. 1 may be considered typical of the majority of preloaded systems with tie-rods normally found in machines and installations.

To evaluate the effect of the external load, the preloaded system of Fig. 1 can be considered. Due to the preload the tie-rod is stretched and the spacers compressed; the total amount of their deformation is the interference of the connection. When an external force F is applied to the ends of the system the two springs, (tie-rod and spacers) are loaded in parallel.

Since the lengthening resulting from the load must be the same for both, the force transmitted by each of them is directly proportional to its stiffness. These portions of force superimposed on (added to) the preloading give the overall force transmitted by each spring.

The system reacts to the external forces applied in this way with a stiffness equal to the total of the stiffnesses of the two springs.

The stiffness ratios instead determine the distribution of the external load between the two elements of the system. This fact can be advantageously exploited to limit load variation on the threads; it is sufficient for the tie-rod to be very elastic in comparison to the spacers.

Obviously elasticizing of the tie-rod must not take place to the detriment of the diameter of the thread in the zone of coupling with the nut (critical point), so that the specific loads deriving from external forces are effectively lowered at that point.

In general, especially in the presence of cyclic loads, it is advisable for the design engineer to position the thread within the sphere of the elastic system so as to minimize the effect on it of the external load ($\Delta\sigma$). It is well known that screw threads due to their high notch coefficient, have a fatigue strength limit ($\Delta\sigma_{lim}$) that is very low in comparison to that of a smooth bar of the same material (Fig. 5), and are in general the most critical points of a machine technology (rolled threads, ground threads etc.) or of design (tensile nuts, specially shaped threads etc.) aimed at improving the fatigue strength of connections, while they may substantially increase the $\Delta\sigma_{lim}$, can change the situation illustrated in Fig. 5 only slightly.

The above line of reasoning is also pertinent to the case in which the external load is not applied to the end of the connection.

In relation to these simple examples, emphasis should be laid, as a general concept, on the importance for the fatigue performance of a threaded connection of the points of application of the loads and of their mutual positions in respect to the threads. The latter should be in positions «protected» from external loads in order to minimize the relevant .

All of this is however subordinate to the presence of adequate preloading and to its long-term stability. The preloading must be such as to keep the system monolithic (without detachment or sliding between contact surfaces of different components) during application of the load. The higher is the interference, the more reliable is the long-term persistence of this condition.

In addition, no part of the system must exceed the yield point, as this would be equivalent to a decrease in interference and in preloading.

If preloading should be eliminated in the system shown in Fig. 1, the entire external load would be discharged onto the tie-rod.

Since in general the safety coefficient ($\frac{\Delta \sigma_{lim}}{\Delta \sigma}$) is insufficient to cover such an increase in stress, in the presence of cyclic load the result would be breakage of the tie-rod. Moreover, if the external load on the thread, devoid of preloading, should change direction at each cycle, there would be impacts on the threads and an ulterior significant decrease in the resistance limit.

In summary, threaded connections can withstand high static loads (at most, even slightly higher than the yield point), but their resistance to cyclic loads is very low and is practically independent of the mean stress level (Fig. 5).

Adequate, well-calibrated preloading is the indispensable condition for the correct functioning and strength of a threaded connection that must work in fatigue conditions, insofar as this factor, along with correct engineering of the elastic system, results in low stress excursions on the thread in the presence of high excursion of the external forces to which the connection is subjected.

Hydraulic tightening is a method that helps to achieve this objective, allowing optimum utilization of materials even with threads of large diameter.

ACKNOWLEDGEMENTS

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ELEMENTARY CONNECTION WITH AN ELASTIC BOLT

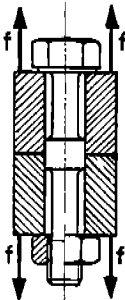


Fig. 1

HYDRAULIC JACK MOUNTED ON END OF TIE ROD WITH TENSILE NUT

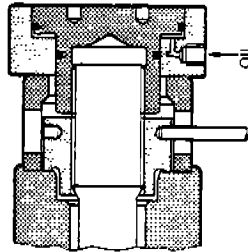


Fig. 2

ROD/CROSSHEAD HYDRAULIC CONNECTION SYSTEM

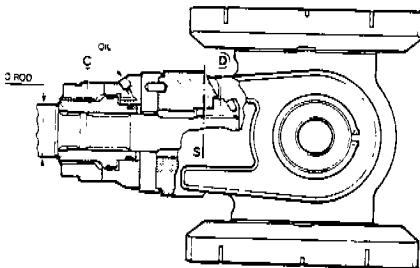


Fig. 3

CONVENTIONAL ROD/CROSSHEAD CONNECTION SYSTEM

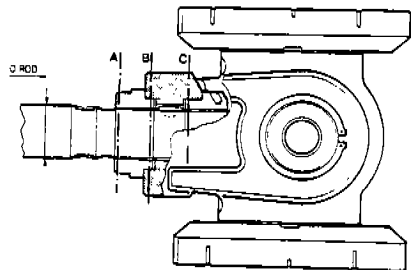


Fig. 4

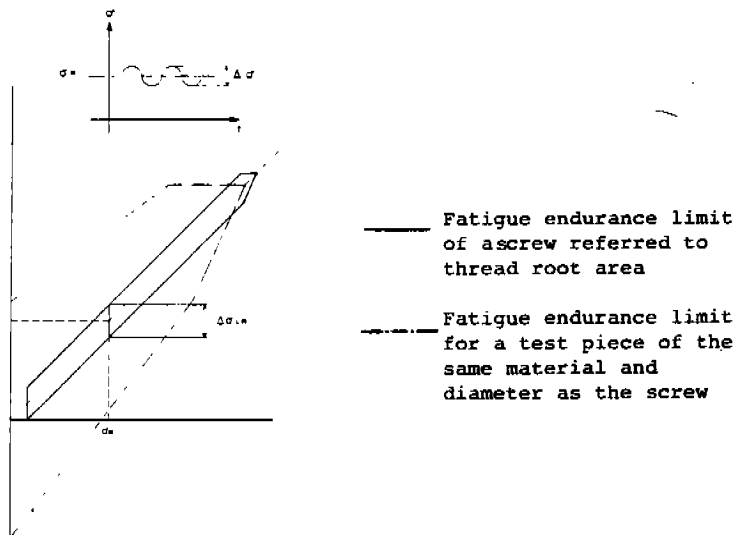


Fig. 5 - FATIGUE ENDURANCE LIMIT OF A THREADED CONNECTION

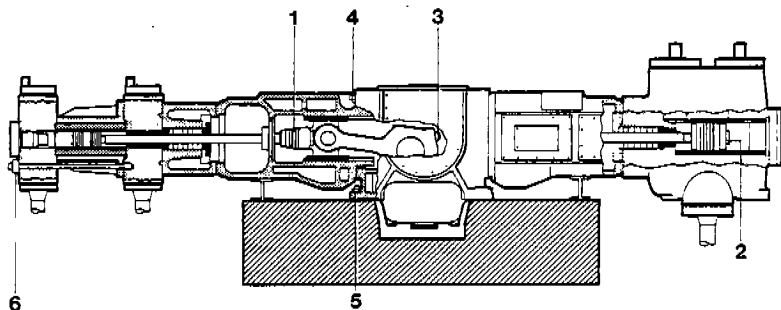


Fig. 6 - APPLICATIONS OF HYDRAULIC TIGHTENING ON RECIPROCATING COMPRESSORS

Ref. Fig. 6 mark	Connection	Reasons for using hydraulic tightening
1	Rod/Crosshead	1 2 3 5 6
2	Rod/Piston	1 2 6
3	Big end of connecting rod tie rods	1 2 3 4 5 6
4	Frame crosspiece tie rods	2 4 6
5	Anchor bolts	2 6
6	High pressure cylinder linkage	1 2 4 6

LEGEND:

- 1) Precision of preloading
- 2) Amount of preloading
- 3) Poor accessibility
- 4) Simultaneous tightening
- 5) Optimum utilization of material
- 6) Increased reliability

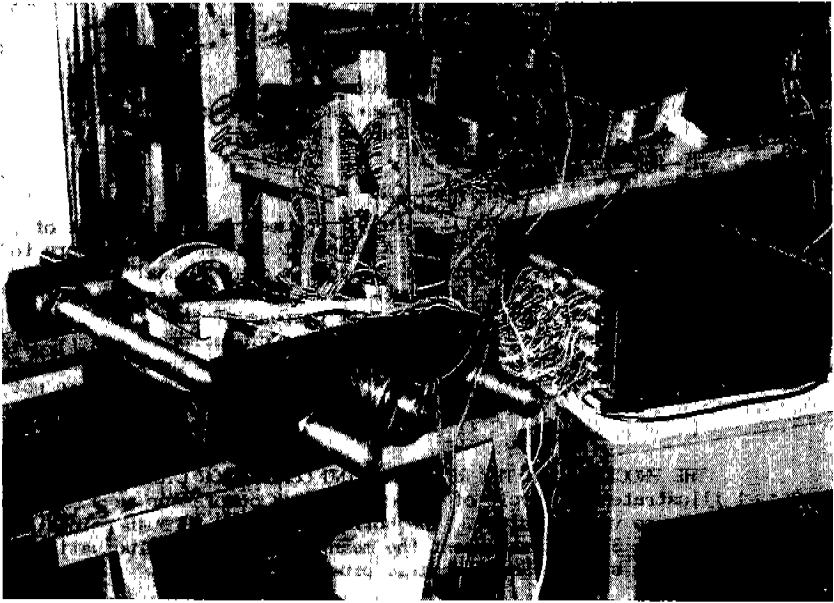


Fig. 7 - STRAIN GAUGE TESTS ON ROD/CROSSHEAD HYDRAULIC CONNECTION SYSTEM

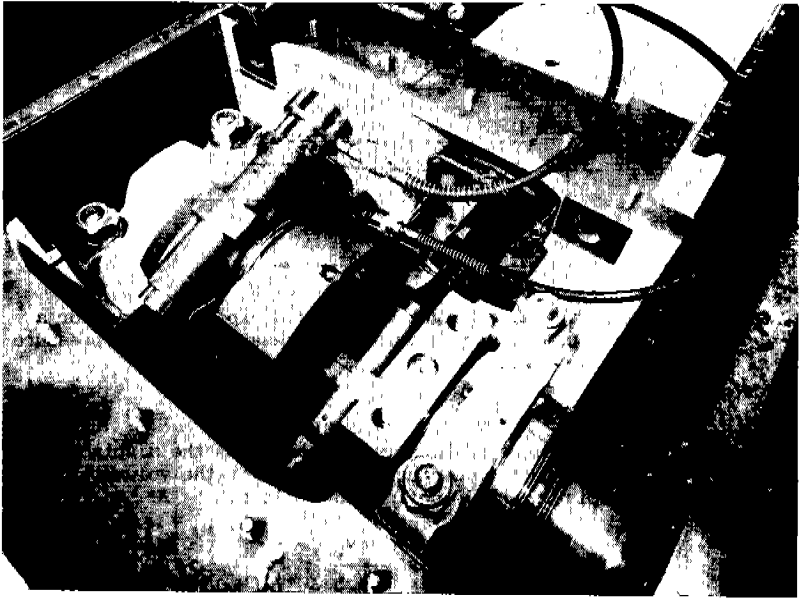


Fig. 8 - SIMULTANEOUS TIGHTENING OF TWO TIE-RODS OF CONNECTING ROD BIG END