6.

THE ATTACHMENT OF ROTOR DISCS IN IMPULSE TURBINES.

The impulse turbine is characterised by the fact that the conversions of heat into kinetic energy take place in the nozzles, instead of partly in the fixed and partly in the moving blades, as in reaction turbines. This difference in principle entails marked divergencies in the design of the two types, the chief being that the impulse turbine consists of a series of compartments separated from each other by diaphragms, between which a number of distinct rotor elements revolve, while in the reaction type each rotor may consist of a single drum revolving in one compartment. The rotor elements of the impulse machine are necessarily connected to the one rotor shaft, and in order to economise in length the disc construction becomes the obvious design to be adopted.

In designing a disc there are two general objectives, namely :—

(1) That the part shall be strong enough to resist the stresses induced by its rotation, and that it shall be sufficiently rigid and suitably proportioned to ensure that undesirable vibrations are not set up under working conditions, and

(2) That its attachment to the rotor shaft shall be strong enough to transmit the required horse-power, while remaining entirely secure and concentric with the shaft axis at all speeds.

In the early design of direct-coupled impulse turbines, where low revolutions were imposed by considerations of propulsive efficiency, the " wheel " diameters were large, and these parts were generally built up of steel plates between which the hub and rim castings were bolted. These were cheaper to manufacture than large discs, and ample stiffness was ensured by providing suitable webs between the plates.

The situation as regards the modern high-speed turbine with heavily loaded discs of small diameter is, however, somewhat different, and a built-up construction is not practicable in such cases, where solid discs become an essential feature of the designs.

A parallel-sided solid disc is subjected to considerably less stress than is the case in a drum of the same diameter, rotating at the same speed : in other words, such a disc may be run up to speeds some 55 per cent, greater than that of a revolving ring or drum, if the same maximum stress is to be reached in both cases. Unfortunately, the discs used for turbines must be provided with central holes for the purpose of fixing them to the shaft, and the general effect of such holes is to render the discs very little stronger than rings.

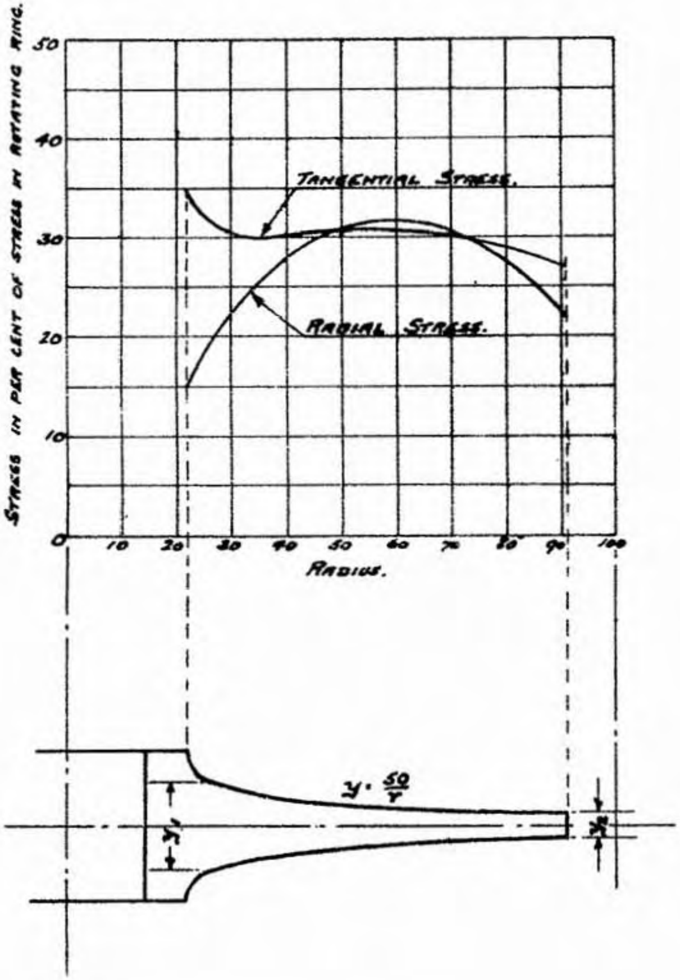

FIGURE 1.

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A plain disc form is not strong enough for modern impulse turbines of powers such as are required for ship propulsion, and it is therefore necessary to increase its strength, which may be done in one of two ways, viz. :—

(1) Strengthening the disc near the periphery of the hole by means of a boss construction.

(2) Increasing the thickness of the disc towards the centre in order to obtain as nearly as possible a uniform strength throughout.

In practice both these solutions are generally adopted to varying degrees, most turbine wheels being provided with a boss of appreciable length, while the disc section is tapered from root to rim. The discs are provided with rims to form an attachment for the blading, and the centrifugal load depends upon the weights of these items and upon their peripheral speeds, varying as the square of the latter factor.

Mathematicians have not yet discovered any simple method of estimating the stresses in a turbine wheel of given shape, but the general theory underlying that process is now well understood and various approximations are available giving results sufficiently refined for practical design. In the usual form of turbine disc the thickness is small compared with the diameter, and on that account it has been found permissible to consider only two main stresses, viz., the radial stress and the hoop or tangential stress, in the mathematical analysis of such a system : the axial stress and the shear stress are therefore neglected with a consequent simplification of the analysis, which is, in any case, sufficiently complicated.

It is not proposed in this article to deal with the mathematics of the subject or to give any method of practical design, but if the latter is desired for any particular purpose reference may be made to an article in "Engineering," 9th August, 1919, by H. Haerle, of Messrs. Reavell & Co., Ltd., as providing one of the most simple and readiest methods available. The classical researches of Stodola will be found in his book "Steam and Gas Turbines," while one practical deduction therefrom has been suggested by Professor Goudie in his work entitled "Steam Turbines."

The curves in Fig. 1 indicate the estimated distribution of the radial and tangential stresses in a wheel of the form shown, the stresses being shown as percentages of those in a plain disc of the same radius. The stresses are, in general, reasonably determinate throughout the wheel section except at the fillets joining the disc proper to the hub, but some uncertainty exists as to the extent to which the whole length of the hub can be considered as contributing to the strength of the part : the effect of the keyway is also somewhat doubtful as the existence of this may increase the effective bore of the hub by an indeterminate amount.

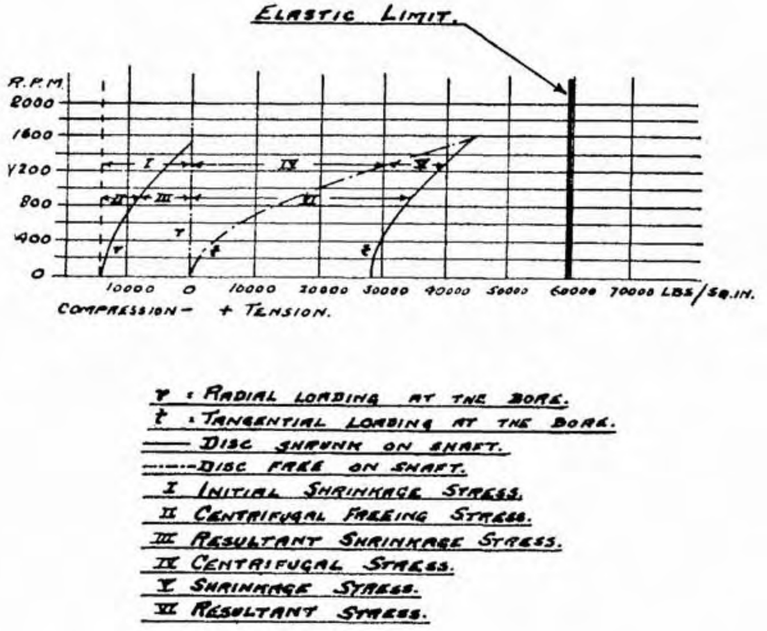

FIG. 2.

The effect of the centrifugal load, when running at speed, is to stretch the hub, thus loosening its fit upon the shaft. The hub is therefore initially made a "forced fit" upon the shaft, the amount the bore of the hub is made smaller than the diameter of the shaft being arranged so that the stretch of the former is not greater at any speed than the compression given by the forced fit: the wheel consequently remains a close fit upon the shaft.

The curves of Fig. 2 show how the stress at the bore of the hub in a particular case is varied as the speed is increased. In this instance the initial "force fit" gives rise to a compressive stress of 14,000 lbs. per sq. in. when the wheel is standing. The centrifugal stress at the bore gradually rises as the speed is increased, the difference between this stress and that due to the original "forced fit" becoming correspondingly less and less. Finally, at a speed of 1,500 r.p.m., these two stresses become equal and the nett stress at the bore is therefore zero, the original grip between the wheel and the hub thus having entirely disappeared: the wheel will become loose on the spindle at speeds above 1,500 r.p.m. when the centrifugal stress becomes predominant.

In considering the design of hubs, it must be borne in mind that Naval turbines are invariably subjected to an overspeed test carried out at revolutions 15 per cent. in excess of those corresponding to the full power. It may be noted that the overspeed test applied in all turbines built before 1925 was

20 per cent. in excess of full power revolutions, but a reduction in this requirement has been permitted in order that higher stresses may be worked to at full power, so enabling the weight of the turbine to be reduced. Some divergence of opinion exists among turbine manufacturers as to the amount of damage likely to occur if a wheel becomes loose for the short period of an overspeed test, but, as such an irregularity may prejudice the subsequent security of the attachment, it is highly desirable that some degrèe of forced fit should be provided under all conditions of running, including the overspeed, a minimum figure of about one-thousandth of an inch (radially) being a reasonable provision.

The designer requires, however, to know what are the limits of " forced fit " that can safely be provided, and consideration of this question makes it evident that under normal circumstances the shrinkage stress in the hub should not exceed the elastic limit of the material: if this permitted, then there is danger of plastic flow occurring at the bore of the hub, which may then become loose, or alternatively the material may fail through overstressing at high speeds. Experiments* which have been made on wheels of this type show that for the usual form of hub, and with a solid shaft, the bore is expanded about two-thirds and the shaft is compressed about one-third of the total forced fit. If, however, the shaft is hollow, the proportionate strain of the hub decreases as the hole in the shaft is increased; thus for ratios $\frac{\text{internal}}{\text{external}}$ diameter equal to $0 \cdot 5$, the compression of the shaft and expansion of the hub are about equal. This fact makes it possible to arrange for a large force fit without causing permanent strain of the material at the inner circumference of the hub.

It has been found in practice that for steel on steel it is not desirable to exceed a forced fit of about one-thousandth of an inch per inch diameter of the bore in light discs of the type used in current naval practice; greater " pinches " than this not only involve a risk of permanent strain but also may cause buckling of the wheel rim. This latter type of distortion arises from the fact that in the static condition the web portion of the disc is acting as a strut in compression between the solid hub and the comparatively stiff rim; in common with other struts, it may be subject to a " critical " load which is not determinable by any simple calculation, but which, in the usual forms of disc, is apparently likely to be approached with force fits appreciably exceeding the limit referred to above. Buckling of this nature usually shows itself in the form of a wave at the rim of the disc, which thus appears to run " out of truth." It is evident, however, that the distortion should disappear when the turbine

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* " Increase of Bore of High Speed Wheels," by S. A. Moss, *Journal Amer. Soc. Mech. Engrs.*, September, 1912.

revolutions reach a point such that the compressive stress in the web is below the critical. This effect, while it may possibly cause some minor vibration at low speeds, should not in general result in any serious damage, as it should disappear at the highest speeds when trouble from unbalanced forces is likely to be most pronounced. In the light of existing knowledge, it appears unnecessary, and even imprudent, to make any attempt to " true " up a buckled disc of this type by machining it while in place on the hub, but a wheel of a new or advanced design which shows marked distortion may well be removed from its hub in order to test whether the true form is regained on release of the forced fit. Circumstances, such as exceptionally high speeds or very heavy blading, may require the adoption of larger " pinches " than the maximum figure quoted above, and this difficulty has been overcome in some cases by fitting bronze bushes on the shaft in way of the hubs : the bronze then takes a greater proportion of the pinch than the steel hub, and so enables larger forced fits to be applied.

It will be appreciated on examining Fig. 1 that the stress in the hub is a maximum at the inner circumference, and gradually decreases towards the exterior. Thus, if the maximum stress in a wheel is not permitted to exceed a definite figure, it is evident that a great part of the material is not stressed up to this limit; economy in weight might, therefore, be obtained if a means could be found of constraining these comparatively idle fibres to take a greater share of the load.

An ingenious method of partially achieving this object has been used to some extent, especially in Continental shore practice, though not in Naval designs. This is known as " overspeeding " or " mean-stressing," and briefly consists in subjecting the disc before the machining of the bore and other surfaces has been completed, to an overspeed run at revolutions some 50 per cent. in excess of those corresponding to the normal full power.

The wheel is designed so that the effect of this action would be to subject the fibres at the bore of the hub to a stress exceed- the elastic limit. When this limit is reached, however, some slight permanent strain of the inner fibres occurs, with the result that additional stress is thrown upon the next layer of material : this latter in turn yields slightly, and the process proceeds till the mean stress in the hub is appreciably raised, without any great degree of permanent strain having arisen.

The wheel is now finish turned and bored, being thereafter fitted to the hub in the usual way. The slight relative internal adjustments of the fibres consequent upon this treatment will have so disposed them that the stress distribution in the hub is altered and levelled up throughout the working range (and well above it also). It may be noted that this operation actually raises the elastic limit of the material at the inner part of the hub, and that the value of this limit evidently will vary from a maximum at the bore to the normal elsewhere. The inner fibres are, of course, somewhat hardened by this treatment, but it should be noted that, although a slight permanent set has occurred, the material remains fully elastic provided that the process has not been carried too far. A typical stress-strain curve for a steel, such as that used in the manufacture of turbine wheels, is shown in Fig. 3 to illustrate how the action just described is enabled to proceed: the effect of increasing the load above the elastic limit, removing it and then applying it once more is clearly evident.

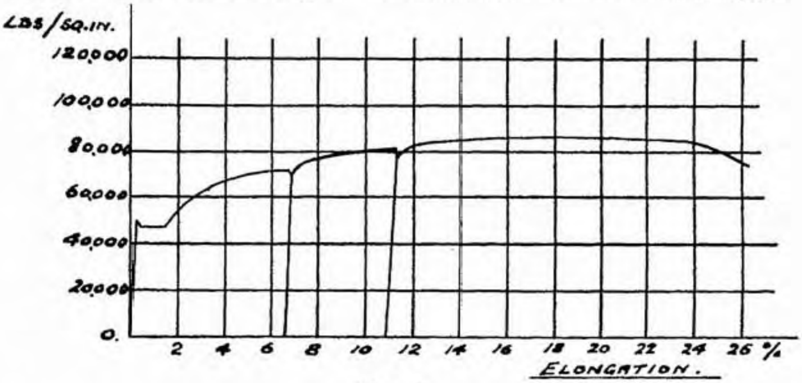

Fig. 3.

Method of Fitting.—The shafts and hubs of the impulse turbines in most Naval designs are both made to a definite taper and are fitted together by hand till the wheel engages with the shaft within a predetermined distance from the shoulder up against which the hub is designed to bear when in the working position. If the taper is accurately known it is a simple matter to calculate what this distance should be in order to give any desired expansion of the bore of the hub and compression of the shaft. This axial distance is known as the "draw" and defines the amount of forced fit actually employed.

The following description of the method used at the Works of one large firm for ensuring that the designed conditions are actually obtained, may be of general interest. The turbine spindles are formed in a series of steps of decreasing diameter, thus enabling the wheels to be readily placed in their respective positions; each step forms a shoulder up against which the end of the hub is designed to bear. The operation of turning the shaft can be more accurately performed than that of boring the wheel hub, and as a first step therefore, the bore of the hub is machined to finished dimensions, the other parts of the hub being merely rough turned and grooved. The machining of the bore is accomplished by the aid of a taper gauge made from ½ inch plate, this being required to enter the hub till a 10/1,000 inch feeler just enters at S (Fig.4)—this ensures that the maximum diameter of the bore is a shade on the small side. The bore is then gauged at points (say) half-an-inch from each end and, assuming the axial draw to be X inches, the shaft is turned to these gauges at points A and B (Fig. 5) at the distances shown from the shoulder.

The additional $\frac{1}{8}$ inch included in these dimensions is to ensure that at the first attempt there shall be no risk of turning the shaft too small.

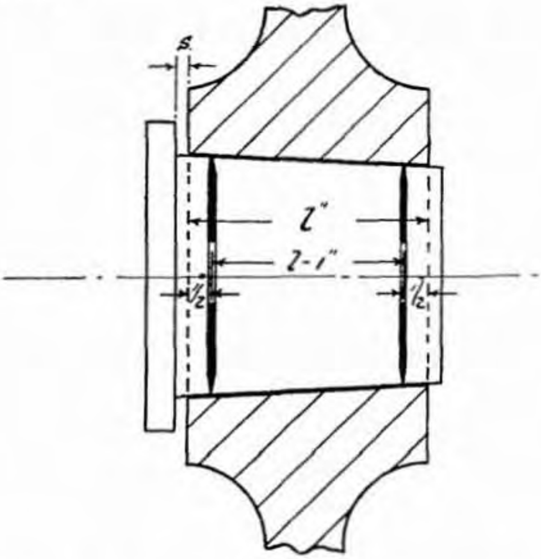

Fig. 4.

The wheel is now pushed on by hand and the available "draw" is measured. The shaft is then carefully reduced by fitting and scraping until the wheel can be pushed on to give the designed draw.

The accuracy with which this dimension can be gauged and repeated on subsequent attempts has been demonstrated, the maximum probable variation being of the order of 1/32 inch with first-class workmanship: this means that it is reasonable to calculate force fits to the nearest 0·001 inch, as the above limit of accuracy represents a change in diameter of only

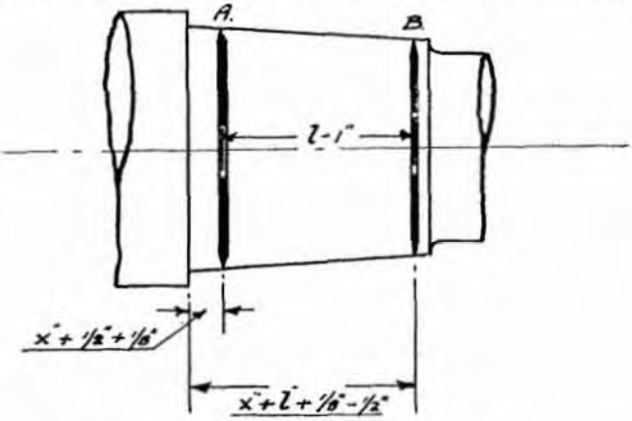

Fig. 5.

0·00065 inch on a taper of 1 in 48. When the wheels have been individually fitted in this manner, the whole series is forced on to a position ¼ inch short of their final position. Heat is then applied to the wheels, which are thus expanded sufficiently to enable them to be readily " bumped " home. It is evident that if the operation is to be carried out in this manner, then the axial draws must approximate to the same figure in each wheel; this can usually be arranged, but results in some variation in the stresses in the various hubs. It is the practice at this particular Works to finish—turn, groove and blade the wheels on their respective shaft lengths, and this requires that they should subsequently be withdrawn for individual balancing. Holes are provided in the discs for purposes of withdrawal, as, although this operation is possible without holes, the use of jacks between the wheels for such a purpose involves a danger of buckling the wheels and is to be avoided.

It must be appreciated, however, that the provision of any hole whatever in the surface of a rotor wheel involves a concentration of stress at such positions, and in order to avoid local cracking of the discs it is usual to drill the holes as near to the root as possible and to arrange that they shall not entirely penetrate the disc. There is no evidence, as far as is known, to show that holes of this nature have ever been the direct cause of failure of turbine wheels, but fractures due to other effects have generally passed through such holes, which are evidently a real source of weakness.

The actual method of forcing the discs home varies in different works, and in many cases where the pinch is small it has not been considered necessary to resort to preliminary heating of the wheel for this purpose. In the more modern designs of turbine where shrinkages of 20 thousandths of an inch or more are necessary it becomes essential to apply heat to the wheels, some firms expanding the bore till the whole shrinkage allowance has been provided, while in other cases a combination of forced fit and shrinkage is employed. This is effected in some works by directing gas jets upon the hub of the wheel and allowing the heat to extend gradually to the rim, while in other cases the jets are arranged to play upon the sides and periphery of the rim : it is stated that the latter process results in more uniform heating and less risk of distortion. Other manufacturers heat the wheel both near the hub and also well out on the rim, while the use of sheet iron covers to equalise the temperature during the operation is fairly general. The best method of all appears to be that adopted by one well-known firm whose practice it is to heat the discs in a bath of boiling water, in which they are immersed for a sufficient period to ensure that all parts attain a uniform temperature; the disc is then immediately forced on to the spindle by hydraulic pressure and held in position till it has cooled off; little force is required for this operation as it can generally be arranged that the whole of the pinch is removed at a temperature corresponding to the boiling point of water. In order to ensure uniform cooling, it is desirable to refrain from shrinking on more than (say) two discs per 24 hours.

It is evident that, whatever the method employed, uniformity of heating and cooling is of great importance; in this connection the not infrequent practice of quenching the discs by cold water spray after they are home is not entirely to be recommended, although it is evident that little harm should arise on this account provided that the disc is uniformly heated to the comparatively low temperature which is required. Serious stresses are only likely to be experienced if the temperature differences between the various parts of the disc are excessive.

The actual temperature to which the disc should be heated depends, of course, upon the force fit and the diameter of the spindle, but need not in general exceed that corresponding to a rise of about 200° F. in order to expand the hubs by the whole shrinkage allowance, c.f. pinch of ·001 inch per inch diameter and coefficient of expansion of ·00000636 inch per inch length per 1°F. temperature difference. It does not appear to be the practice to measure the temperature of the disc, which is merely heated until it can readily be placed in position on the spindle and finally forced home, if the latter operation is necessary.

One practical point may be of interest, namely, that a radial clearance of about ·002 inch is provided over the tops of the keys, which are inserted in the shaft when the heated discs are being put on: this precaution has been stated by some firms to be absolutely necessary in order to prevent the wheels from binding on the keys.

Repairs to Rotor Wheels.

In the course of repairs to rotor wheels, *e.g.*, re-blading, it frequently becomes necessary to remove these from their spindles, and in such a case it is essential that steps should be taken to ensure their replacement with a known amount of forced fit.

When a wheel has to be removed after having been on service it is desirable to heat it before it is drawn back by means of a strong back, as there is appreciable risk of distorting the wheel or damaging the surfaces of the spindle and of the bore of the hub if large forces are exerted for withdrawal purposes. The uniform heating of the discs is of great importance and is at the same time more difficult than the similar operation carried out prior to placing them in position on the spindle. The use of portable blow pipes, supplied with coal gas and compressed air, is a frequent practice: two operators at least are employed, one standing on each side of the rotor spindle, the blow pipes being manipulated to heat the wheel as uniformly and as quickly as possible. While the wheel is being heated a steady pull is maintained on the withdrawing screws by screwing up the nuts against a strong back placed across the end of the turbine spindle.

It does not appear to be usual to supply any cooling medium to the spindle during the process of heating the wheels, but if the spindle becomes heated before the wheel is removed it is essential to cool both rotor and spindle before re-heating; a light blast of compressed air is frequently used for this purpose.

The condition of the bearing surfaces between the hub and the spindle is tested by means of red lead markings, and if necessary these parts are cleaned up and refitted, care being taken to remove the smallest possible amounts of material in the process. The wheel is then tried on the spindle to ascertain how far up on the taper it will go when cold, the remaining draw being carefully measured and compared with the designed figure shown on the drawings.

The bore of the wheel and the diameter of the shaft seat should be carefully gauged in order to check what the actual pinch will be, the measurements being taken across the two diameters at right angles at both ends of the seat.

It is usually found that, provided the wheel has not been stretched by overspeeding, heating at the diaphragm glands or other causes, it will go back very closely to the position which it originally occupied. In cases, however, where the actual "pinch" is less than that designed, or if in the original design the allowance was not such that some positive "pinch" would remain at overspeed, it may be necessary to adopt some device such as bushing the hub or building up the spindle by means of welding or electro-deposition.

The use of welding for this purpose has been satisfactorily employed in some mercantile marine repairs, but it is not to be entirely recommended in view of the possibility of prejudicing the strength of the spindle, parts of which are likely to attain the dangerous condition known as a "blue heat" during this process: thorough annealing would doubtless remove this objection, which, however, has always to be borne in mind when considering the use of welding in repairing steel parts. Electro-deposition can usually be relied upon for building up parts of this nature provided that it is applied by experts in the process, in which case the attachment of the coating should be all that can be desired, while any minor imperfections in its continuity should be of little importance for such repairs.

A sketch (Fig. 6) of a method of bushing employed by one firm is included for information.

It is obvious that each case of this nature requires individual treatment, but *the same essential requirement must be provided for in every instance, namely, that the original forced fit must be duplicated*: if this is not possible, then a calculation is required to ascertain the safe maximum speed at which the turbine can be run without the stresses due to rotation exceeding those due to the available forced fit, that is without entirely removing the positive grip of the hub upon the spindle. It need hardly be stated, in view of what has already been said, that the function of the keys is to transmit the torque which is not designed to be taken by the force fit remaining in the hub at speed, although this latter may, in many instances, be fully capable of doing so.

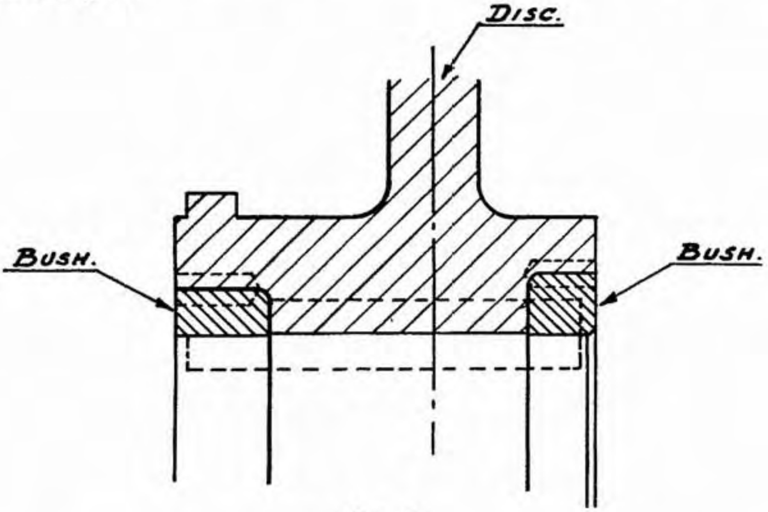

FIG. 6.

The use of disc type rotors has in recent years been extended to the reaction turbine, where drum formation was universally adopted in the early form. This change has been effected for two reasons, first because the drum does not permit of the high blade speeds necessary in modern designs and secondly because discs are, on the whole, somewhat cheaper to manufacture than drums.

The rotor discs used in Parsons L.P. turbines are very similar to the impulse type, but are characterised by comparatively wide rims, while the hubs are of the same length as the former : this heavy rim loading results in a spindle of large diameter, while the radial depth of the disc proper is considerably smaller than in the usual impulse wheels. It is customary among many manufacturers of these turbines to make the wheel seats parallel instead of coned, but the method of attachment by shrinkage and by keys is the same : the keys are frequently round topped.

Different types of attachment.—This article would not be complete without some mention of other methods of disc attachment, the first of those to be described being in many respects ideal. In this design, made by Messrs. Metropolitan Vickers, Ltd., the disc is secured either by rivets or by fitted bolts to a flange forged solid with the shaft. The great advantage of this method is that the rotational stresses at the centre of the wheel can be calculated with very fair accuracy as they are uncomplicated by shrinkage stresses whose value can only be known very approximately. The stress in the attachment is taken by the rivets or bolts in shear and given suitable scantlings and good workmanship there is no fear of looseness at any speed. The design is, however, somewhat heavier than the normal type and can only be applied to one or two wheels, the final L.P. and initial H.P. ones being those usually selected.

The rotating discs in the A.E.G. turbine (German) are generally supported on coned bushes. The distance which these will enter the hub is determined with a moderate pressing at a preliminary assembly, after which they are forced deeper into the heated disc with enough allowance to give the predetermined shrinkage. The design is indicated in Fig. 7 in which it will be seen that the bushes are threaded internally to provide for withdrawal: a sleeve is arranged between adjacent hubs to form part of the diaphragm gland.

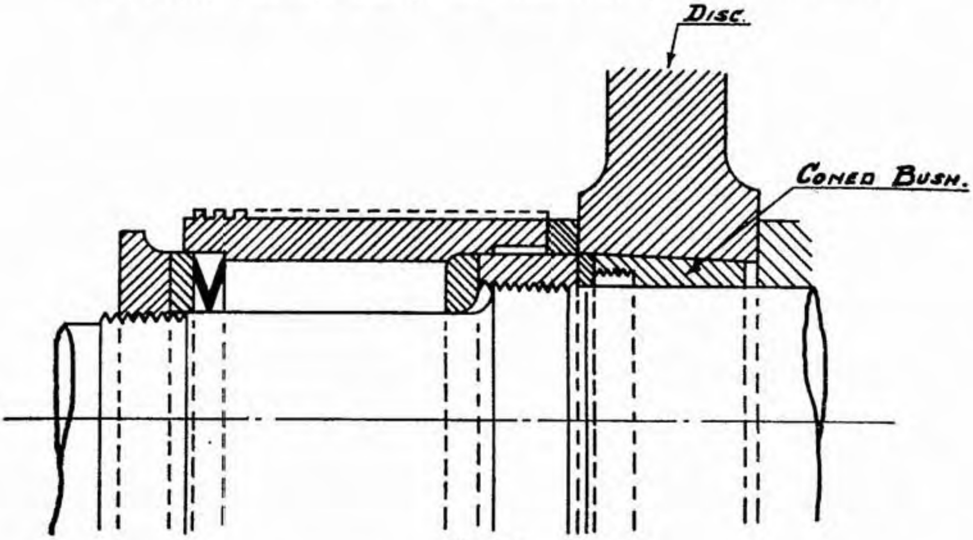

Fig. 7.

The principal advantages of this method are that not only can the strain of the hub for a given forced fit be lessened by employing bronze bushes, but also the task of threading the wheels over the spindle is somewhat simplified on account of the increased clearance between the latter and the inner circumference of the hub.

A somewhat similar method of attachment to that of A.E.G. is indicated in Figs. 6 and 8, and a description of this may be of interest as examples are to be found in some Service types of turbo generators.

The wheel is an easy fit (0.002 inch clearance) on the spindle and has recesses turned at each end of the hub. Split rings of steel or bronze are provided, these being initially a close fit (+ 1½ thousandths,–¾ thousandths) upon the shaft, while their outside diameters exceed the dimensions of the recesses in the hub by a predetermined amount.

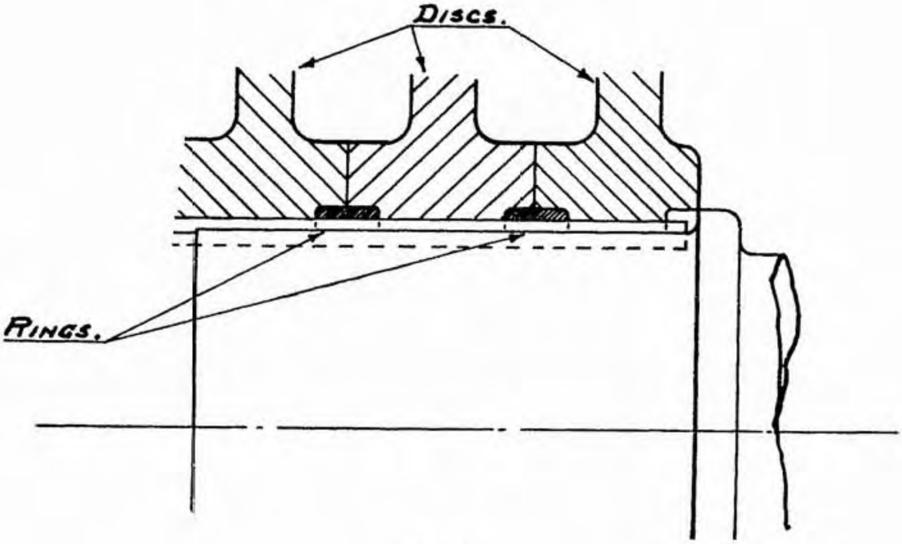

FIG. 8.

The split rings are forced into the hub recesses after the wheel has been placed upon the spindle, and are thus initially stressed to an extent which is calculated to be sufficient to prevent any looseness occurring owing to the expansion of the bore of the hub at speed. The driving torque is taken by keys fitted to the hub in the usual manner.

The wheels are removed by forcing off by means of strongbacks; the split rings may be subsequently withdrawn, holes being drilled in the rings for attaching any extracting gear which proves to be necessary

The modern tendency in the design of impulse turbines is towards an increased number of stages with a consequent decrease in their mean diameter. This arrangement is favourable for the use of solid rotors, in which the wheels and spindles are formed in one from the same ingot, thus avoiding the difficulties in connection with the attachment of the former parts. This type of construction has not as yet found a place in marine practice, chiefly on account of considerations of length, but, as it is particularly suited for use in turbines working with ultra-high steam pressures, it is likely to be adopted if and when turbines working under these latter conditions are fitted in marine installations.

Causes of loose wheels.—In conclusion it may be of interest to enumerate briefly the factors which may lead to a forced fit, of the type described, becoming loosened. These are but three, namely, overspeeding, local heating of the hub by rubbing at the diaphragm gland and, finally, heating of the rim extending to the hub while the shaft remains comparatively cold.

Rubbing at the diaphragm gland may be caused by distortion of either the spindle or of the casing, the latter being most likely to occur when steam is admitted to parts of the circumference only, especially when the inlet belts are not situated at the ends of the turbine. Distortion of the casing may also be caused during the warming up period if the steam is not admitted evenly around the circumference of the cylinder. Thus, if steam is admitted at the upper part, this will be heated to a temperature of about 212° F., while in the lower part, due to the descending cooled condensate, the temperature may be much lower. This effect will result in upward bulging of the casing, which carries the diaphragms with it and so causes absorption of the clearances in the glands. Damage should not result from such an action provided that the casing attains an even temperature before the rotor is permitted to revolve, but the danger is present and must be guarded against.

Distortion of the spindle when it is at working temperature may arise from the effects of unsuspected internal flaws and improper heat treatment (*i.e.*, forging is in a state of internal stress), and to avoid this possibility one large firm makes a practice of heating the spindle while it is rotating between centres, under which conditions certain specified limits of distortion may not be exceeded. Insufficient clearance at the diaphragm glands, improper adjustment of the bearings or excessive vibration of the spindle will, of course, cause rubbing at these glands, but should not exist in well designed and properly constructed turbines.

Heating of the wheel as a whole, while the shaft remains cool, may possibly occur when rapid changes of speed are made, and is especially to be anticipated in the initial stages of the H.P. turbines: in such circumstances as these, the hub becomes expanded and the grip on the shaft may be reduced to such an extent that the wheel becomes loose. It is interesting to note that the opposite effect may be experienced in the final L.P. stages when turbines are first started: under this condition the temperature of the L.P. is commonly well above the working temperature of the steam and thus the wheel tends to be cooled at the rim, with the result that compressive stresses are set up in the web, which may be buckled to some extent.

All these effects will show themselves as vibration and are, of course, temporary ones, which should disappear if the conditions of working are suitably modified: they are, however, mentioned here as providing possible explanations of events which may otherwise not be understood.