THESIS

on

Governors

MAY 15th, 1875.

A Few Notes on Governors and their Principles of Action.

by Wilfred Lewis.

As soon as the steam engine was invented it was found necessary that some means be devised for giving it a uniform motion.

Sudden variations could be controlled by the fly wheel but still the effect of an increased or diminished load would become apparent in a change of speed in the engine, and to obviate this difficulty Watt conceived the idea of making this change of speed itself a means of regulating the supply of energy to the engine, and for this purpose he invented the Steam Engine Governor.

Since then, the modifications of this simple device have been almost as varied as those of the steam engine itself and even now, we can scarcely pick up any scientific journal in which some new improvement in this direction is not to be found. It would seem from these improvements which have been constantly going on since its invention, almost a century ago, that it must have reached perfection by this time, and for most purposes it is hard to imagine how better governors could be invented, but the different forms and principles which can be combined in them, are almost unlimited, and each has its own peculiar advantage either in durability, first cost, simplicity, sensitiveness or whatever it may be. Many of these good qualities can only be determined by trial or experience, while those only which depend on the principles on which the governor operates can be seen at first from a working drawing or by a study of the governor itself, and it is mainly these latter which I shall attempt to consider.

As the steam engine and machinery became more perfect, the use of the governor became more and more extended and now it is found connected with the regulator of almost all prime movers; the only exceptions being those, in which, like marine engines, the speed is controlled by the increasing resistance due to an increase of speed or, as in locomotives by the judgment of the engineer.

The simplest of all, and one that is still considerably used is an application

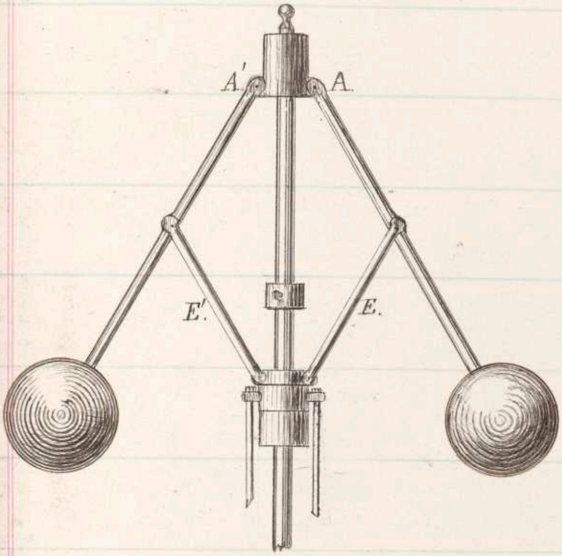


FIG. 1.

of the revolving pendulum. It is the original invention of Watt and consists, as shown in the figure of two heavy pendulums which are made to revolve about a vertical spindle. As they rise or fall they communicate their motion to a collar on the spindle by means of the rods E.E'. which are jointed to the ball-rods in such a way that each is always parallel to the opposite ball-rod, thus forming a parallelogram in which the spindle is a diagonal. In all calculations concerning this governor the point from which the pendulum is suspended must be considered as the intersection of the axis of rotation with the centre line of the ball-rod and the distance from this point to the centre of the ball as the length of the revolving pendulum. This length of course varies when the joints A.A'. are far from the axis, but usually it may be taken as constant and equal to that found for the mean position of the balls. In general, this governor can be virtually represented by the centre lines shown in fig. 2. and may be considered as nothing more than two simple pendulums, the weight of the ball-rods being neglected. There are various

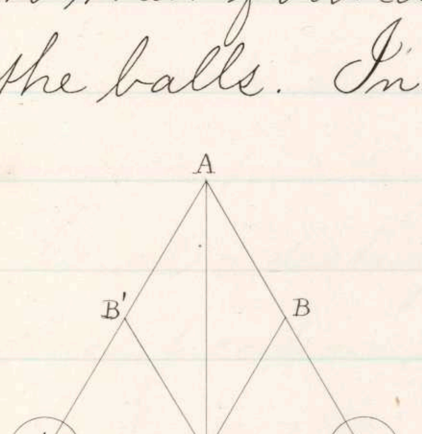


FIG. 2.

general distinctions by which all governors may be classified. Prof. Rankine in his "Machinery and Mill Work" divides them under the following three heads - Position govs. Disengagement govs. and Differential govs. and according to this classification, the pendulum and most other govs. come under the first head, which he defines thus - "A position governor is one in which the moving piece that acts on the regulator, assumes positions depending on the speed of motion." He also distinguishes them by another classification into Gravity govs. and Balanced govs.; and still further into those which are truly isochronous and those which are nearly so; and again into those which are specially adapted to one speed and those which can be adjusted at will to different speeds. He also makes another distinction, which separates all the foregoing classifications from the Fly-governor, which is used to prevent sudden variations of speed, without attempting to preserve a uniform speed, and which he does not consider as a governor proper.

By a gravity governor is meant one in which the centrifugal force is opposed by the force of gravity, and a balanced gov. is one in which the actions of gravity on the various moving parts are mutually balanced and the centrifugal force is opposed by the elasticity of a spring.

As before stated the object of a steam governor is to maintain the engine at a constant speed and the best governor is clearly the one that reaches this end in the simplest manner. The question then is, does the pendulum governor maintain the engine at a constant speed under all circumstances which are likely to occur? is it absolutely or only approximately constant? and if approx., on what does its degree of approximation depend and how can the variation in speed be reduced? Suppose, for example, we have a governor as shown in fig. 2. the collar D being connected directly with the throttle valve, which moves without friction from fully open to fully closed a distance of, say 4 in. It is attached to an engine which, when overcoming a certain resistance makes sixty revolutions per minute, the valve being at the same time in its middle position, or capable of moving 2 in. in either direction. Now, supposing that the average steam pressure in the cylinder is proportional to the opening of the throttle valve, and that the speed of the governor is equal to the speed of the engine, we wish to find at what speed the engine must run when overcoming double, and half the normal resistance. In the figure AB = BC = BD and consequently AD = the height of the revolving pendulum below its point of suspension, which we will call h. Considering the collar and all weights supported by it as balanced by a counterweight we see that AC is the resultant of two forces, the weight, and centrifugal force represented respectively by $AD = h$ and $DC = r$ and hence we have the relation $\frac{h}{r} = \frac{\text{weight}}{\text{centrifugal force}} = \frac{W}{\frac{W}{g}\frac{v^2}{r}} = \frac{gr}{v^2}$ in which v is the velocity of rotation, and g the acceleration of gravity per second. Calling T the number of turns per second, $v = 2\pi r T$ and substituting we have $h = \frac{g}{4\pi^2 T^2}$ which makes h depend entirely upon T. Therefore when $T = 1$ or 60 revs. per min. $h = 9.78$ in. and by transforming the equation $h = \frac{g}{4\pi^2 T^2}$ into $T = \sqrt{\frac{g}{4\pi^2 h}}$ we find, making $h = 9.78 + 2$ and $9.78 - 1$ respectively that $T = .91$ and 1.06 or in other words that the speed varies from about 55 revs. per min. under heavy load to 64 under light load which is about 15% of the normal speed. It appears from the formula just deduced that the less we make the throw of the valve or the motion of the collar the less will be the variation in speed, and we find in the above example, if the throttle valve had had an opening 2 in. long instead of 4 in. the variation in speed would have been about 7% and if this valve had been connected with the collar in such a way as to move through twice the distance moved through by the collar, the variation would have been reduced to about 4%. Thus, by neglecting all resistances to be overcome by the collar, this variation in speed can theoretically be brought within any assignable limits and the governor be made very delicate, but at the same time should any sudden change of speed occur before it has time to act, the fluctuations in speed will be greater and continue longer than if it were less sensitive. Theoretically, in the case supposed without friction or resistance to the collar, these fluctuations would continue indefinitely but they are practically overcome by the use of a dash-pot, which, while it prevents a quick motion of the valve, opposes very little resistance to a slow motion and thus holds it in its proper mean position. This governor, therefore is at best only an approximate regulator, even when all friction and the resistance on the collar are entirely overcome, but practically this can never be the case and the effect of such resistances remains to be considered. When no resistance is to be overcome, it matters not what the weight of the revolving mass may be, but when there is an appreciable amount its disturbing effect depends upon the weight of the balls, and can be lessened but never eliminated by increasing that weight.

In the previous example, suppose the weight of each ball had been 50 lbs. and the resistance offered by the valve to motion in either direction had been 6 lbs. to find what increase or diminution of speed is necessary to to move it in either direction.

The resistance being 6 lbs. it follows that the downward force acting at the centre of each ball varies from (50 + 3) lbs. to (50 - 3) lbs. and upon the value of this force the value of a in the formula $T' = \sqrt{\frac{a}{4\pi^2 h}}$ depends, for, when the downward force equals the weight, a is constant and equal to g, the acceleration produced by a force of 50 lbs acting on a weight of 50 lbs. but, when another force acts on a weight of 50 lbs. the acceleration varies proportionally to that force. Hence for a we can substitute its greatest and least values $\frac{53}{50}g$. and $\frac{47}{50}g$. and calculate T for any value of h. And we find, when the valve is in its mean position that the speed can vary about 6% without producing any change on the regulator, and if the speed, as in the first case, had varied 15% without any resistance on the collar, it now varies 20% from light to heavy load. Calling R the resistance to the motion of the collar, $c = \frac{AB}{AC}$ a constant by which R is multiplied to determine the force transmitted to the centre of each ball, and W the weight of each ball we have the general equation $T'^2 = \frac{\frac{W \pm cR}{W} g}{4\pi^2 h}$ which solved relatively to W gives $W = \frac{gcR}{T'^2 4\pi^2 h \sim g}$ an expression in which $4\pi^2 h = \frac{g}{T^2}$ T being the speed corresponding to the height h for a simple pendulum and T' any assumed speed which is considered as not differing too greatly from T.

Substituting the value of $4\pi^2 k$ we have the equation $W = \dfrac{gCR}{\left(\frac{T'}{T}\right)^2 g - g} = \dfrac{CR}{\left(\frac{T'}{T}\right)^2 - 1}$ which gives a simple means of finding W when we know R and decide upon the change in speed which can be allowed for overcoming it. Thus, suppose for example, that R, as before, = 6 lbs. $c = \frac{1}{2}$ and that we do not want the speed to increase or decrease more than one per cent without moving the collar. The necessary weight W will then be found by substitution as follows – $W = \dfrac{3 \text{ lbs.}}{(1.01)^2 - 1}$ or $\dfrac{3 \text{ lbs}}{1 - (.99)^2}$ = 149.25 lbs. or 150.75 lbs. The larger weight, being required to prevent the decrease in speed, should be used, but either result or the mean 150 lbs is sufficiently correct.

It thus appears that when the resistance R is considerable, the weight W must be very great indeed to give a nice amount of regularity and on this account the pendulum gov. is not well adapted to overcoming great resistances such as the raising of a sluice gate by the direct action of the collar. In fact, as stated by Morin, many failures have been made in attempting to do this but the same end is now accomplished by simply converting this governor into a disengagement gov.; that is, by using it merely as the means of bringing some other power into play, by causing it to shift a belt from a loose to a fixed pulley, for instance, or connect two shafts.

The loaded pendulum governor, an instance of which is seen in Porter's governor, is more sensitive than the common form, but still not truly isochronous. The principle of it can be seen from fig. 3. The load W is a solid of revolution about the vertical axis AC, and is hung directly from the balls by a pair of links equal in length to the ball-rods. The vertical spindle upon which the weight can have a vertical motion passes through its centre and supports the whole revolving mass from the pt. A.

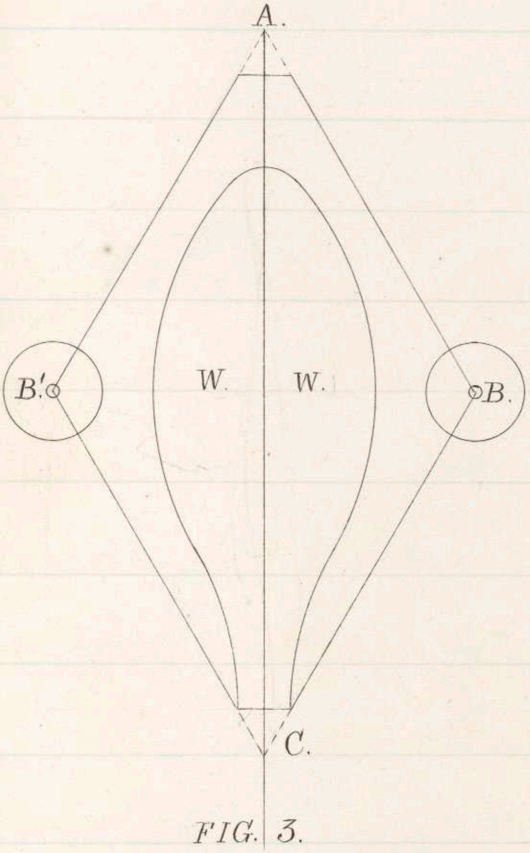


FIG. 3.

Calling w the weight of each ball, and W the weight of the load, the downward force acting on each ball is $(W+w)$ and consequently we have the equation $h = \frac{W+w}{w} \cdot \frac{g}{4\pi^2 T^2}$; the height h being greater than that due to a simple pendulum in the proportion of $(W+w)$ to w. From this it follows that the vertical motion of the collar for any difference in speed will be correspondingly greater, and, that therefore, the same vertical motion will be produced by a much less variation in speed, showing, as already stated, that this is more sensitive than the common pendulum governor. If the sensitiveness of a gov. be considered proportional to the distance through which the collar moves for a given variation in speed it will be seen that this is more sensitive than the common form in the proportion of $2(W+w)$ to w. At the Arlington Cotton mills in Lawrence a governor of this kind is used on their Allen engine and has given perfect satisfaction. The load was at first a solid piece of cast iron, but it was afterwards replaced by a hollow casting which was filled with lead to increase the weight. Instead of operating upon a throttle valve in the ordinary way, it is, in this case, connected with a link, worked by two eccentrics, and by changing its position, the throw of the valve is increased or diminished, thus regulating the supply of steam by the more economical method of a variable cut-off. The speed of this governor is greater for a given altitude h than it is for a simple pendulum in the ratio $\sqrt{W+w} : \sqrt{w}$ and when the mean value of h is determined from the dimensions of the parts the necessary speed can be found by the formula $T = \sqrt{\frac{W+w}{w} \cdot \frac{g}{4\pi^2 h}}$. The principle, upon which the two governors already mentioned, depend for their action is the controling force in almost all governors, but the way in which motion is communicated to the regulator is varied considerably in detail. In Judson's governor, Fig. 4. the balls are hung from the points A.A' at quite a distance from the axis. The ball-rods continue to the collar D on the valve stem, and are slightly bent at the points of suspension. When at rest, the balls are supported at an angle of about 45° by the stops C C'. The collar, in this case, instead of moving through a distance proportional to the height moved through by the

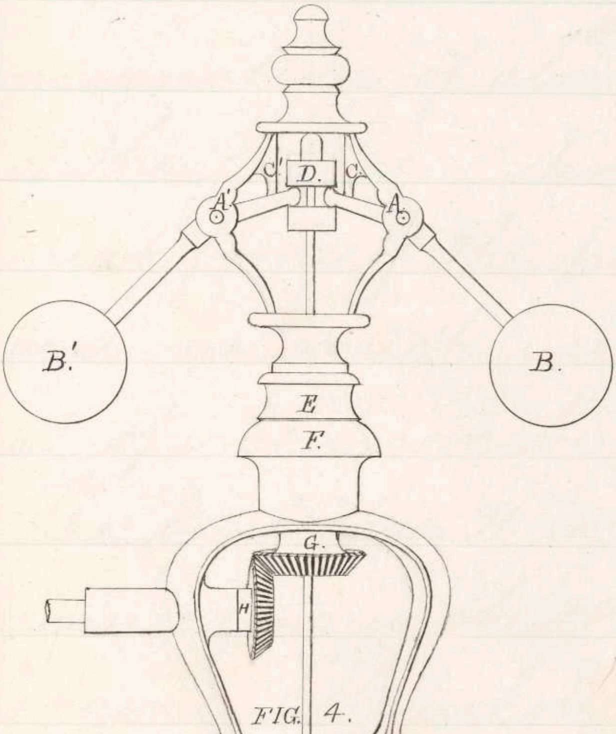


FIG. 4.

pendulum, moves approximately through a distance proportional to the arc moved through by the pendulum, and, while this would tend to increase the sensitiveness, the obliquity at which the balls swing, and the distance of the points A.A'. from the axis tend to decrease it, so that practically it is found that this governor allows a variation of about 8% in the speed of the engine. Nevertheless it is a very neat form of the pendulum governor and one much used. The way in which it operates can be seen from the figure. The bevel gear H is made to revolve by connection with the main shaft of the engine. The whole upper part of the gov. above F is connected, and revolves with the bevel gear G, and the valve rod passes down through the centre of the gov. and adjusts the throttle, (not shown, in the figure).

As the balls fly outward, the effect

of any increase in speed is less apparent in the motion of the collar, and

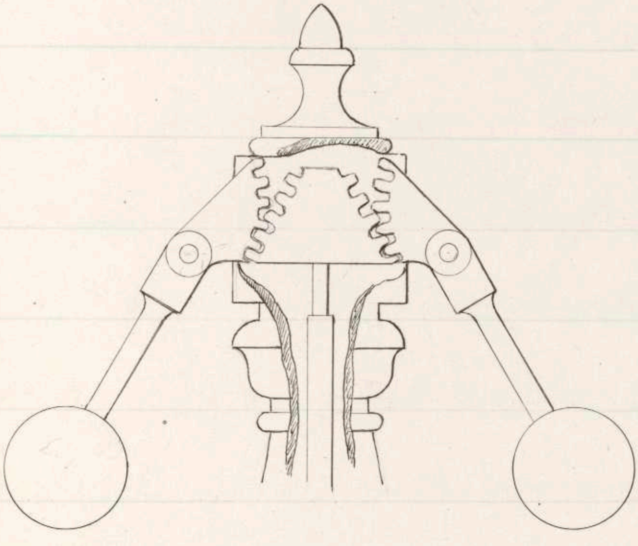


FIG. 5.

to compensate for this defect an arrangement similar to what is shown in fig. 5 has been invented. The ball arms are provided with cam shaped ends which gear into a wedge shaped block on the valve rod, and it will be seen that as the balls expand from centrifugal force the cams are increasing their leverage in their downward movement, giving increased travel to the valve and compensating for the decreasing movement of the balls as they approach a straight line.

In practice, a truly isochronous governor is seldom if ever met with, although a few would be so if their construction were perfect and all friction overcome, still, the greater part of those now in use and those which are from time to time brought into notice have not, in their construction, any principle of true isochronism. The reason is, most probably, that for most purposes to which the governor is applied, a close approximation to a certain speed is all that is desired, and when this can be obtained by a simple, durable and cheap device it is, of course, useless to spend more money for anything better. But the need of perfectly uniform motion must be continually increasing and when a governor can be made on true principles of isochronism, at a much less cost than many of the complicated and expensive instruments which are only approximate, it seems strange that inventive genius should be turned so much toward making instruments as near as possible to perfection on imperfect principles when it is as easy to work on true principles and aim at absolute perfection. There may be, however, many practical considerations which do not appear in the theoretical discussion of the subject, but which are of great importance in designing or constructing, and since the success or value of many instruments is due, in a great measure, to the practical experience of the inventor, it is but fair to suppose that in governors, as in most everything else, only an imperfect knoweledge of the subject can be got from the theory, and that by one of my inexperience, for instance, the real merit of some governors is often unappreciated, while again the faults of others are unnoticed. I do not mean to say however that true theory differs from actual practice, for what is considered practical knoweledge becomes theoretical when properly understood and the relations of cause and effect established, but simply this, that there are two ways of learning the same truths either in the abstract from books, or, by actual experience in the workshop, and that neither method alone is apt to be entirely satisfactory or free from error. Thus, while theory alone would lead us to believe Rankine's Isochronous Gravity governor and some others to be absolutely perfect, we find a host of later inventions which claim to be unequalled and unexcelled by all others, but which are, at the same time, theoretically unable to maintain an engine at a uniform speed. The last mentioned governor, shown in fig. 5, is one of these, and the inventor in an article describing it in the "Scientific American" for Sep. 10 - 1870, makes the following observations, which, allowing for personal bias, may be taken as the result of his experience and study upon this subject. "One would think" he says "from the great variety of steam govs. and regulators in market that the true principles of governing steam and regulating steam engines have been reached and that the field for further improvement has been well nigh exhausted.

But the keen observer and the experienced engineer as well as the manufacturer who is affected by the need of perfect motion and regular speed of machinery, know that there still lies open a great want for improvement yet unattained in the steam governor.

It is well known, however, to those conversant with steam, its subtle nature and its application to power that there are many difficulties and obstacles to encounter in obtaining uniform motion, and, to compensate for the ever varying powers required for the steam engine, inventors have brought forward numerous combinations of improvements, many of which embrace radical points of convenience and novelty but which are more or less actuated by auxiliaries, such as weights, levers, or springs, to compensate for the seeming imperfections in their principles, and their application thus rendering them more or less complicated with a multiplicity of parts, making them difficult to adjust and operate, and lessening their reliability and durability." And, it is no doubt true that simplicity is of the greatest practical importance; while, theoretically it is not generally taken into account. He still goes on to say that the centrifugal-ball principle has been found by practice to be the most reliable means of showing variation in speed; and also that however perfect the governor may be in construction it becomes of little use when applied to an imperfect valve used for regulating the supply of steam, and that one of the great considerations is to have a perfectly constructed cut-off valve combined with the governor. It may be however a question of as great or greater difficulty to decide what is a perfect regulator as to say which of all the unequalled and unexcelled governors is the best, and, inasmuch as the governor, independent of the regulator is the subject of this thesis, it may be well, when no other valve is mentioned, to consider the governor, as operating upon the one here described, which, if not perfect, can probably claim to be unexcelled, at least.

"The valve, fig. 6 consists of a series of rings secured by internal ribs thus forming ports for the admission of steam from the chamber B. This valve slides in a chamber C having ports corresponding to those in the valve

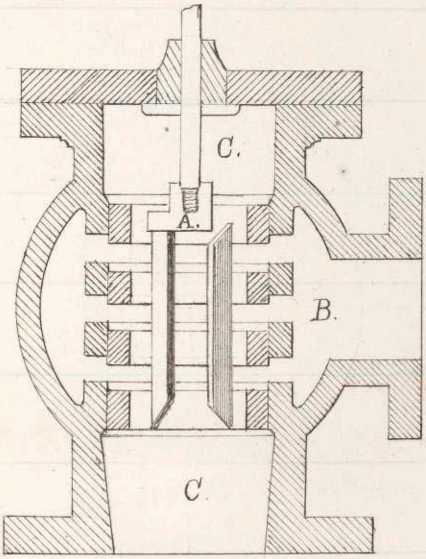


FIG. 6.

and the rings forming these ports are stayed by ribs on the outside corresponding to those in the valve. As the valve is moved longitudinally in its seat it will be seen that the steam from the chamber B may be entirely cut off by its movement in either direction and that being surrounded by steam it is perfectly balanced and works without pressure to retard its motion." The object of having the steam cut off by a movement in either direction is that the valve may act as a stop in any case of accident, for example, the breaking of the belt, in which case the balls drop and cut off the steam by an upward movement of the valve. Some such safe guard against the engine running away is usual on the best governors, but, if it is not thought worth while to guard against such an occurrence it is an easy matter to so adjust the length of the valve stem that the ports may be open when the engine is at rest, as is more frequently the case.

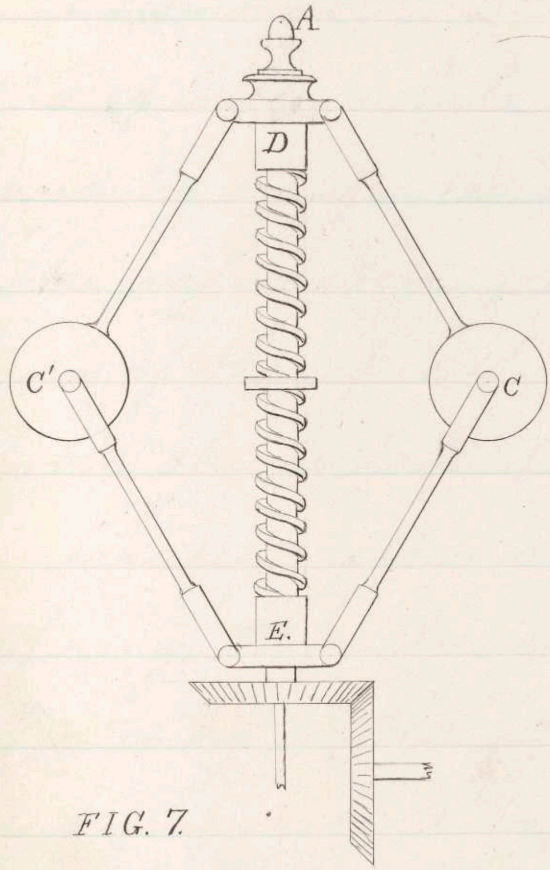


FIG. 7.

With regard to govs. actuated by springs a very curious example is seen in the adjoining figure, in which it appears to me that the spiral spring, obviously intended as an improvement, decreases rather than increases the sensitiveness. In the "Scientific American" for Jan 6 - 1872, an engraving of this gov. is given but in the accompanying article such great importance is given to the manner in which it stops the engine when the belt breaks, that the supposed advantages of the spiral spring are not mentioned at all. The collar E is fast to the spindle, while D slides easily upon it and is supported by the spiral spring. The valve stem passes through the axis of the spindle and receives its motion from the collard D which, as the speed increases descends compressing the spring. The force of the spring, corresponding to the weight in Porter's governor, is transmitted to the centre of each pendulum. When the governor is at rest the compression in the spring is equal to the weight of either ball, but when in motion the excess of this compression is the force which acting at the centre of either ball produces a moment about the point A which is equal to the moment of the centrifugal force about the same point.

Now when the stress on the spring is doubled, or when this excess becomes equal to the weight of one ball, the height h assumed by the governor is equal to that assumed by a simple pendulum revolving at the same speed, but, if the speed increases until the stress on the spring is trebled, the height h' assumed by the governor is two times that of a simple pendulum which in comparison can be put $\frac{h'}{2}$. This is evident when we consider that the force, in the couple opposing the moment of the centrifugal force about

about A, is twice as great in one case as in the other and that the centrifugal force is, in both cases, proportional to the lever arm of that couple.
The distances moved through by the collar are proportional to the differences of these heights, and, when the links are equal in length to the ball-rods, as in the figure, we have, for this distance in the spring gov. $2(h - h')$, and, in the ordinary pendulum governor $2(h - \frac{h'}{2})$ which shows, that, in this case, the spring is both practically and theoretically a disadvantage.
The inventor thinks, however, that he has attained a degree of perfection not before attained in a governor, but, in what that perfection consists,

it is hard to tell, unless we suppose that the belt breaks every five or ten minutes, in which case, it would, no doubt, show off to great advantage. The position governors, thus far considered, all allow a certain amount of variation in the speed of the engine, and even when all resistances and friction, are supposed overcome, a certain difference in speed is always necessary to maintain the regulator in any new position.

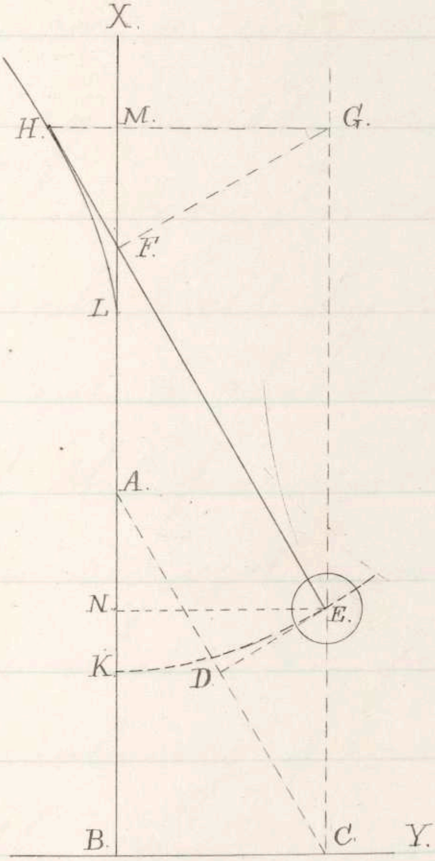


FIG. 8.

The Parabolic pendulum governor (described in Rankine's "Machinery and

(Mill Work") differs from them in this last respect in being perfectly isochronous. The principle of it is shown in fig. 8. The balls revolve about the vertical axis BX and are guided in such a way that in rising or falling they must follow the arc of a parabola. This may be done either by hanging each ball by means of a flexible spring from a cheek of the form of the evolute of the parabola or by supporting them on curved arms of the proper form as shown in fig. 9. The height of a revolving pendulum thus guided is the same in all positions and is equal to the sub-normal of the parabola; from which it is evident that the gov. will be in equilibrium only at one constant fixed speed, and that for all other speeds it will have a continual tendency to shift the position of the valve.

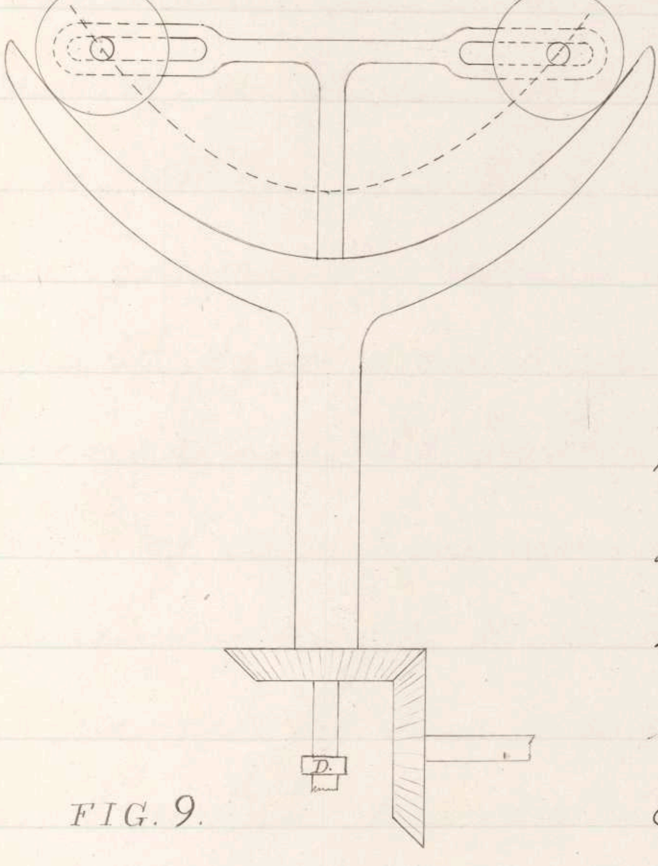


FIG. 9.

To find the force with which this tendency is exerted let W be the weight of the balls and let the acceleration, which could be given to them by this weight plus or minus the resistance they overcome, be represented by a. Then, we know that $k = FN = \frac{a}{4\pi^2 T^2}$ is constant, and that a must vary if T varies and we have for the

value of $\underline{a}$, $a = g = (4\pi^2 h) T^2$ or $a_1 = (4\pi^2 h) T_1^2$.
but we can put $T_1 = (T + t)$ in which t is the increased number of turns per second, and substituting we have
$a_1 = (4\pi^2 h)(T^2 + 2tT + t^2)$ in which t^2 can generally be neglected, as too small to make any appreciable difference in the value of a_1. g is the value of a when no resistance is offered, therefore $\frac{a_1 - g}{g} W$ is the vertical force in excess of the weight of the balls and when the values of a_1 and g are substituted we have for the approximate value of this force,
$F = \frac{2.t.T.}{T^2} W.$ or expressing t in terms of T the ratio of the increase in speed being $\frac{t}{T} = \Delta T$ we have $F = 2\Delta T. W.$
The following is Rankine's graphical

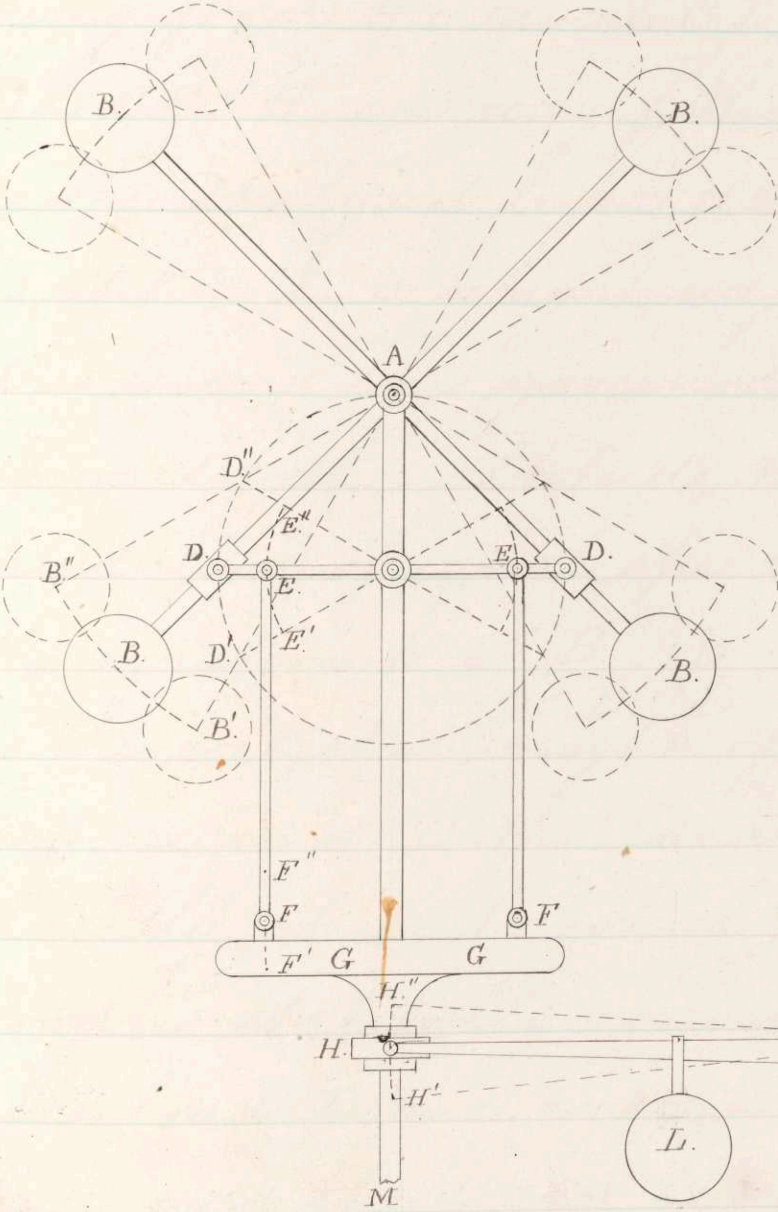
method of finding a series of points in the parabola, and its evolute. Referring to fig. 8. let h be the altitude = FN; then from the vertex K lay off KA = KB = $\frac{1}{2}h$; A will be the focus and the horizontal line BY the directrix. Draw AC parallel to an intended position of the ball rod; bisect it in D, draw DE perpendicular to AC and CE parallel to BX; the intersection E will be a point in the parabola, and ED a tangent. Then parallel to CA, draw EF; this will be a normal and a position of the ball-rod. From F parallel to DE, draw FG, cutting CE produced in G; and from G, parallel to BY, draw GM, cutting EF produced in H; this will be a point in the evolute. When the mean position of the ball rod is assumed this construction also enables us to find the point H from which the pendulum might be hung and give approximately the same result as though it moved exactly in the parabolic arc. H is the centre of the radius of curvature of the parabola at the point E and the correctness of the construction just given can be proved as follows.– Assume the origin of co-ordinates at K, and call a & b the co-ordinates of the centre of the osculatory circle for any point E of the parabola. The equation of the parabola then is $y^2 = 2hx$, h being the sub-normal or twice the focal distance. It is shown by the differential calculus that the general expression for the co-ordinates of the centre of an osculatory circle are respectively $a = x - \frac{\frac{dy}{dx}\left(1+\left(\frac{dy}{dx}\right)^2\right)}{\frac{d^2y}{dx^2}}$ and $b = y + \frac{1+\left(\frac{dy}{dx}\right)^2}{\frac{d^2y}{dx^2}}$.

Substituting the proper differential coefficients derived from the equation $y^2 = 2hx$ we have $a = 3x + h$ and $b = -\frac{y^3}{h^2}$. Also, from the construction we see that $KF = x + h$, and $MF = 2x$ and therefore that $KM = 3x + h = a$. and likewise $HM = -\frac{\overline{MF}^2}{y} = -\frac{4x^2}{y}$ $-\frac{y^4}{h^2 y} = -\frac{y^3}{h^2} = b$.

When the balls are supported upon curved arms as shown in fig. 9., an additional load may be applied to them by a weight acting on the collar D. The governor is then called, a loaded parabolic governor, and, like the loaded pendulum governor at a given altitude, the speed must vary in the ratio of the square roots of the entire loads including the weight of the balls. By changing the load the gov. can be adjusted for any desired speed. The principle of the parabolic governor is very ingeniously carried out in Rankine's Isochronous Gravity-governor, which he describes as follows -

"In this form of governor the four centrifugal balls marked B are balanced as regards gravity, about the joint A, on the spindle AM. D,D are sliders on the ball rods; DC, DC, levers jointed

Rankine's Isochronous Gravity Gov.



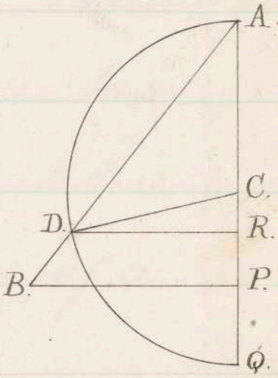


FIG. 11.

FIG. 10.

to the sliders and centred on a point in the spindle at C, and of a length DC = CA ; GG, a loaded circular platform hung from the levers CD, CD, by links EF, EF ; H, an easy fitting collar, jointed to the steelyard lever HK, whose fulcrum is at K ; L, a weight adjustable on this lever. This governor is truly isochronous ; the altitude h of a revolving pendulum of equal speed is given by the equation $h = \frac{B.AB^2}{2D.CD}$; in which B is the collective weight of the centrifugal masses and D the load suspended directly at D, to which the actual load is statically equivalent.

The load D and consequently the altitude and speed can be varied at will by shifting the weight L ; which can be done either by hand or by the engine itself. The regulator may be acted on by the other end of the lever HK. The levers CD, CD should be horizontal in their middle position; and then the ball-rods will slope at angles of 45°. Two positions of the parts of the governor when the rods deviate from their middle, are shown by dotted lines and accented letters. If convenient the links EF, EF may be hung directly from the slides D, D. The theory of the governor is illustrated by fig 11. In any position of the parts, let AC be the axis of rotation; AB a ball-rod carrying a ball at B; C, the point at which the lever CD = CA is jointed to the spindle; D, the central point of the slider, at the end of that lever. About C draw the circle ADQ, cutting the axis of rotation in Q; join DQ; and draw DR and BP perpendicular to AQ.

Then when the position of the parts varies, and the speed is constant, the moment of the centrifugal force of the balls relatively to A varies proportionally to the area of the right-angled triangle APB; and the moment relatively to A of the load which acts on the point D varies proportionally to DR, and therefore to the area of the triangle ADQ; but the areas of the triangles ADQ and ABP bear a constant ratio to each other - viz. that of $\overline{AQ}^2$ to $\overline{AB}^2$; therefore the moment of the load and the moment of the centrifugal force, bear a constant ratio to each other in all positions of the parts of the governor, and if they are equal in one position, they are equal in every position; and if unequal in one position they are unequal in every position. Therefore the governor is truly isochronous".

The formula $h = \frac{B.\overline{AB}^2}{2D.CD}$ can be demonstrated thus by referring to fig. 11. Calling B the collective weight of the balls and D the load, we have the moment of the centrifugal force about $A = \left(\frac{B}{g} 4\pi^2 T^2\right) BP.AP.$ and the moment of the load about the same point $= D.DR = \left(\frac{D}{AQ}\right) DR.AQ$ but these two moments must be equal to each other and since $\frac{\overline{AB}^2}{BP.AP.} = \frac{\overline{AQ}^2}{DR.AQ}$ we can put $\left(\frac{B}{g} 4\pi^2 T^2\right) \overline{AB}^2 = D.AQ$ and because $h = \frac{g}{4\pi^2 T^2}$ we have $\frac{B.\overline{AB}^2}{h} = D.AQ$

Therefore $h = \frac{B.\overline{AB}^2}{D.AQ}$ whence since $AQ = 2CD$ we have the original equation $h = \frac{B.\overline{AB}^2}{2D.CD}$. Since an isochronous gov. is in equilibrium in all positions when running at a constant speed, it is obvious that when it meets with little resistance in moving the regulator and overcoming friction, the momentum in its parts caused by a change in speed might carry them past the point at which they should stand thus causing fluctuations in the speed even while the resistance to the engine remains constant. As before stated, however, this difficulty can always be prevented by the use of the dash-pot, which is nothing more than a loosely fitting piston working in a cylinder full of oil or other liquid.

Among governors which may be considered as isochronous when properly made, might be mentioned Water's spring gov. and the Huntoon gov. both of which are considerably used in New England. Water's governor, fig. 12, works entirely independent of the force of gravity and the centrifugal force of the revolving balls is balanced by the action of springs. We have seen that the centrifugal force due to a constant angular velocity is directly proportional to the distance of the revolving mass from the axis of rotation and therefore all that is necessary to make this governor perfectly isochronous it that the resistance of the spring should vary in the same proportion.

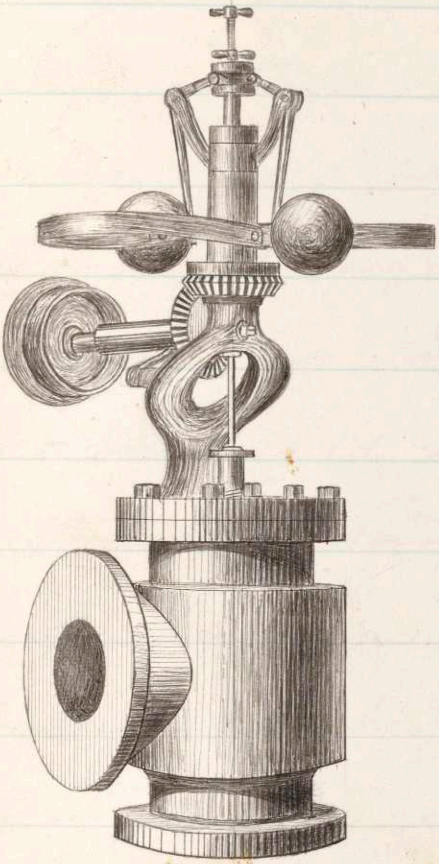


FIG. 12.

As ordinarily constructed, however, this is not the case, and it seems doubtful whether the inventor really intended that it should be, for in his circular he speaks of its being readily adjusted for any speed by altering the length of the valve rod, which at once puts isochronism out of the question. With a spring whose elastic force increases directly as the distance of the centre of the ball from the axis, the speed at which the balls are in equilibrium in all positions can only be varied by changing the weight of the balls; therefore, the gov. should, within reasonable limits accomodate itself to any length of valve-rod without altering the speed. From the manner in which the speed is increased or diminished it appears that the resistance of the spring increases more rapidly than in this simple proportion; but, for most purposes the governor is sufficiently sensitive, and it also has the advantage of being light, compact and of running well in any position, which commends it as a marine fly-governor to prevent the sudden acceleration which would be produced when the propellor screw is lifted out of water. Unlike other governors, the balls do not rise or fall as the speed varies, but have only a horizontal motion. They are supported and rotated by springs shaped something like the letter U and give motion to the collar through the arms shown in the figure. These arms fit loosely into slots in the springs which compensates for all difference in motion as the balls expand. The valve in this governor is said to be perfectly steam balanced and unaffect by the pressure or temperature of the steam. "The valve stem is extended through the collar and furnished with a handle with which to turn it and a check nut to hold it in place. Screwing this stem down causes the engine to run slower, and screwing it up to run faster."

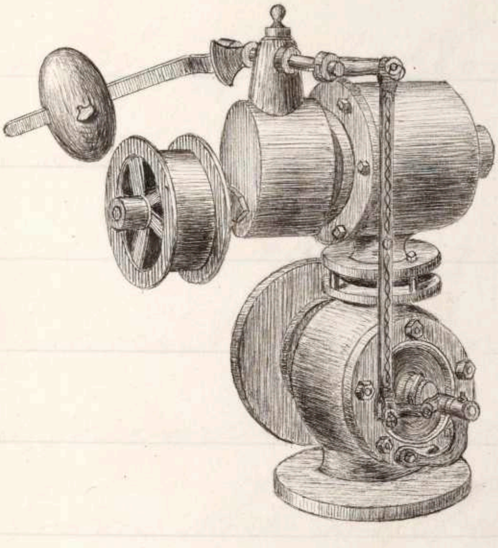


FIG. 13.

The Huntoon Governor might be described as a form of vane gov. the resisting medium being oil. It is shown fig. 13 in perspective and fig. 14 in section. The whole of the upper part of the governor, containing the vane wheel sliding gear &c. is filled with a thin oil or one that does not become viscous at ordinary temperatures. This part is separated from the valve chamber by some non-conducting substance so that the oil may not become too much heated, or, as in the later style air is allowed to circulate between.

When the engine is running, motion is communicated from the belt pulley to the propellor-screw through the small spur wheels. The oil in the case containing the screw is partially prevented from revolving with it by a number of ribs or ridges projecting from the surface. Therefore, as the blades revolve, pressure must be exerted along the shaft against the spoon-lever L; but, this is opposed by the weight on the lever arm M, and, unless the moments of these two forces about the point A are equal to each other, motion will take place in the direction of the greater moment until the valve is so adjusted that the two are equal. The force with which this thrust is

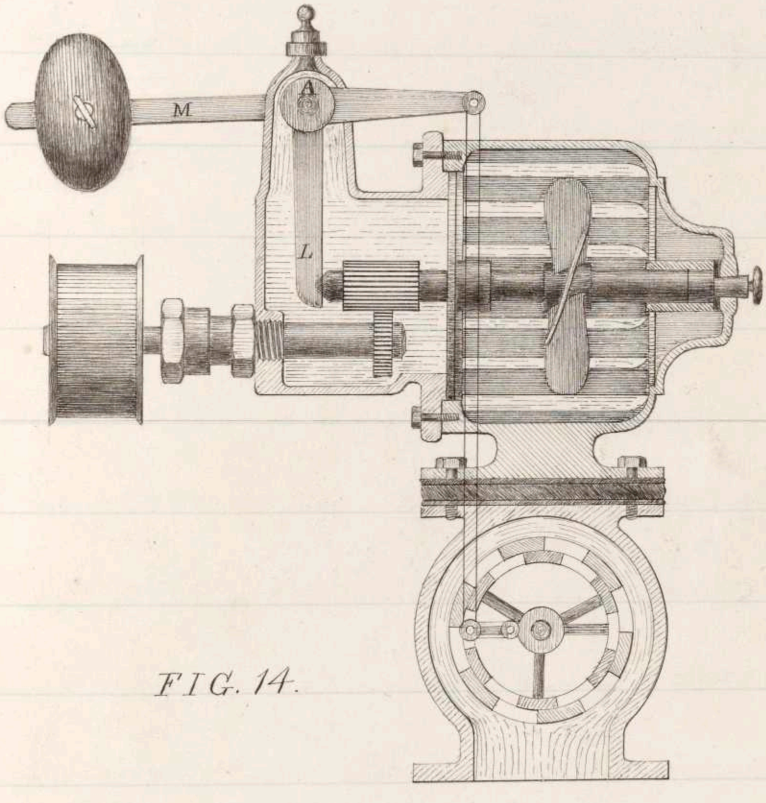


FIG. 14.

exerted against the spoon-lever is proportional to the square of the velocity of the engine, and when friction offers but little resistance this gov. must be very sensitive to minute variations in speed. The case containing the moving parts being full of oil there can be no perceptible resistance to the sliding of the pinion gear and all that remains to cause any disturbing effect is the friction of the valve on its seat. This, however, is reduced to a minimum, and the valve being perfectly steam balanced, always moves when nicely made with the least possible resistance. The only objection which can be raised, against the perfect isochronism of this governor is that the virtual lever arm in the couple produced by the weight does not remain constant. This difficulty could be overcome by suspending the weight from an arc on the lever arm, having A for its centre, but when the mean position of the arm is horizontal it seems almost too critical to make an objection on this account, for then its length is altered only by the versed-sine of a few degrees.

By simply sliding the weight in or out upon the arm the speed of the engine can be varied at will and as easily when in motion as when at rest. The valve used on this governor is similar to the one already described, the ports extending longitudinally instead of transversely and the steam being shut off by a rotary movement of the inner cylinder, instead of vertical. In this way a large port area is secured, while the steam passages can be quickly reduced in area by a slight movement of the governor.

A governor very similar to this called the "hydrostatic governor" is described in the Imperial Cyclopaedia of Machinery, the only essential difference being that the thrust exerted by the vane is resisted by a spiral spring instead of by a dead weight. The resistance of the spiral spring of course increases as it becomes compressed, and since it always requires an increase in speed to compress it further, thereby preventing isochronism, it would seem that Huntoon's arrangement was a

decided improvement.
In the same connection a very peculiar style of governor is described which depends for its action upon the resistance of the air. Four vanes are attached to a vertical spindle which is hollow and fits loosely upon another spindle passing through it. These vanes are suspended from the second spindle by a cord passing through a hole near the top and fastened to the ends of two opposite vanes. Now, when this second stem begins to revolve the cord will partly wind upon it, and set the vanes in motion, and when the speed has so far increased that the resistance of the air is sufficient to cause more of the cord to wind around the spindle, the set of four vanes is raised

thereby and the steam shut off by a connection with the throttle valve. The power of this arrangement to overcome any resistance in the collar must be very small, and from its general appearance it seems as though it might have been invented, like many other things merely as a mechanical curiosity to clutter up a model room and that it could not be used to advantage for any other purpose. The Englishman who writes it up, however, seems to think it's all right and I have no doubt that it is really considered a very good gov. in his country, although the credit of the invention is given to America. Many other kinds of governors are described in this valuable work, which are dependant on a variety of principles. Among them, is one in which the actually transmitted power is taken as the source of the regulating effect, and its operation is precisely like that of a dynamometer. The whole

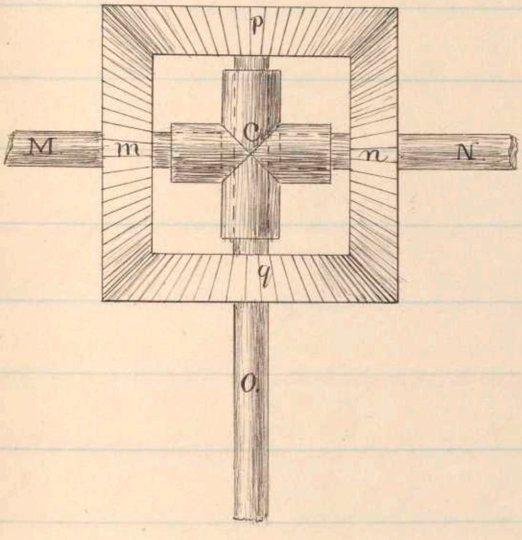


FIG. 15.

power of the engine is transmitted through a set of bevel gears as shown in fig. 15. M. is the main shaft of the engine on which the fly-wheel is placed and N is the shaft to which the power is transmitted through the gears P and q. The gears m and n are fast on the shafts to which they belong while P and q are loose on the shaft O. Now, when power is transmitted a statical moment is produced in the shaft O, which has a tendency to rotate the gears and shaft about the axis MN and this tendency is resisted by a weight or spring on the end of that shaft. When resisted by a spring, the shaft o will assume positions dependant on the power absorbed by the shaft N. and if it is connected with the regulator in the proper way, the energy admitted to the engine will be proportional to the power absorbed and thus this arrangement of four bevel gears can be used both as a dynamometer and governor.

This arrangement could not be used very well on large engines, for, it would necessitate large expensive gearing and the power absorbed in overcoming friction would be considerable; while the noise would be unbearable unless wooden teeth were used and the greatest care taken in shaping and spacing.

Another governor is described which depends upon the pressure of steam in the cylinder or steam chest and another which depends upon the velocity of the steam flowing through the pipes. This last is simply a conical pipe inclined with the large end downwards, and containing a spherical ball. The pipe is curved so that the inclination is greatest at the small end, and as the velocity of the steam increases the ball is driven further and further up the pipe thereby reducing the area of the steam passage, and checking the speed of the engine.

In a governor recently advertised in the Scientific American the pressure of the steam in the steam chest is used as an auxiliary to increase the sensitiveness, and quickness of an ordinary pendulum governor.

In connection with spring governors I should have mentioned a very novel and ingenious device patented by Mr. Hoadley of Lawrence and used on the J. C. Hoadley Portable Steam Engine

It is fastened directly on to the main shaft of the engine close to the fly wheel and operates upon the throw of the eccentric, increasing it as the speed increases and vice versa. The engine is thus controlled by the cut-off and the full boiler pressure is admitted to the cylinder at the beginning of each stroke, which gives, as is well known, a greater efficiency for the amount of steam used. Mr. Hoadley claims that with his engine and cut-off a saving of 50% in fuel may be realized over the common throttle valve engines and his claim is well substantiated by theory, as well as facts.

Many important kinds of governors still remain unnoticed, among them, all differential and disengagement governors; but, having already found the one class of position govs. too much to digest comfortably, I come at once, for the benefit of any one who may labor thus far, to the happy end.