THE CONTROL OF STEAM TURBINES IN THE SUGAR INDUSTRY WITH SPECIAL REFERENCE TO MILL TRAINS

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Abstract

The commissioning of a control system can give fresh insight into the operating characteristics of the driven machinery and thus provide both supplier and user with essential data on the desired control specification for the turbine driver. It can also provide a better understanding of the interaction of the power characteristics of driver and driven machines and the capabilities of the steam turbine.

Introduction

Steam turbines have been used worldwide for many years in the sugar industry as prime movers for many types of plant. Some five years ago Weir Pumps Limited introduced a change in concept of turbine design and at the same time re-appraised the method of controlling and protecting the turbine from undesirable operating conditions.

The range of turbines covered 3 frame sizes, initially designed for use as cargo oil pump drivers both in Petroleum Product Carriers and Large Crude Oil Carriers. Following the successful introduction of the turbines into marine service it was decided to market them to the sugar industry.

The 1-24-2 and 1-18-2 turbines have been used in the sugar industry for up to 25 years now and have proved to be robust versatile machines. However, it was considered that the updated range of units offered the industry a more compact unit for a given range, extending the power ceiling well above that previously available. Thus the present steam turbines are simpler, requiring less maintenance and shorter down times for maintenance and covering a wider power range than the units they replace.

The AET Turbine

The AET (Fig. 1) is an Adaptable Electronic Controlled Turbine. It is adaptable in that the standard unit can be mounted either horizontally or vertically and the control monitoring of the unit is carried out electronically.

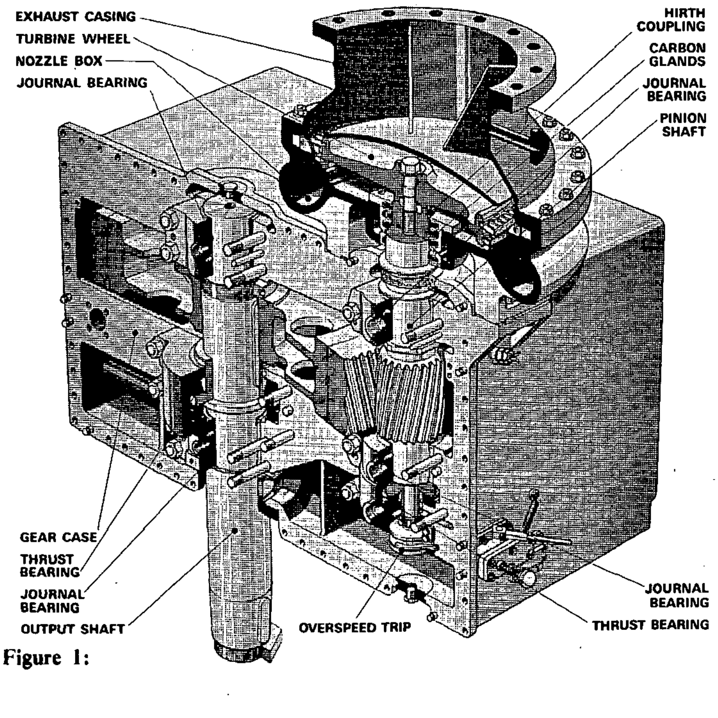


Figure 1:

The design concept was for a simple robust cellular steel box construction gear case containing only the primary reduction train, with no auxiliary gearing to either oil pumps or governing gear. The turbine rotor is a single overhung profiled disc carrying two rows of moving blades. This results in a strong yet light turbine rotor which minimises the loading on the end of the pinion shaft thereby raising its natural transverse frequency of vibration. Figure 2 shows the comparative stress patterns for the Weir Turbine disc against a) a parallel sided disc carrying two rows of turbine blades and b) twin parallel sided discs each carrying one row of blading. The relative masses are also shown.

The more even distribution in disc stresses by using the profiled form is clear and needs no elaboration. The consequential reduction in rotor weight results in higher shaft critical speeds.

Turbine efficiency is related to good nozzle design for expansion of the steam and correct matching of the blade speed to that of the steam leaving the nozzles. The design of turbine nozzles has been carefully researched by us and for the range of steam conditions encountered in our applications we have evolved a series of nozzle profiles that give high efficiencies. Having efficiently expanded the steam, the blade and steam speed ratio must be optimised. Given a set of steam inlet conditions and exhaust pressure, there is one optimum blade speed in metres/second for a given inlet to outlet pressure ratio. It should be noted that this is a linear velocity so that for a rotor, where the peripheral velocity is the product of diameter and speed, the rotor diameter decreases as the rotational speed increases. Rotational speed is not therefore a fixed parameter for either safety or efficiency. Take for example a turbine rotor running at 6 000 rpm, that is 100 revolutions per second, the blade efficiency might be only 60%; when allowed to run at 8 000 rmp, 133 revolutions per second, the blade efficiency might now be 68%, an increase of 8 points or 13%.

The turbine designer therefore has to support the blades at a radius appropriate to the running speed chosen and ensure that the support member, the turbine rotor, is strong enough but not so heavy as to result in an unacceptable shaft critical speed.

Firstly, the blades must be securely attached to the rotor. The most satisfactory arrangement results from careful calculation and photo-elastic stress work.

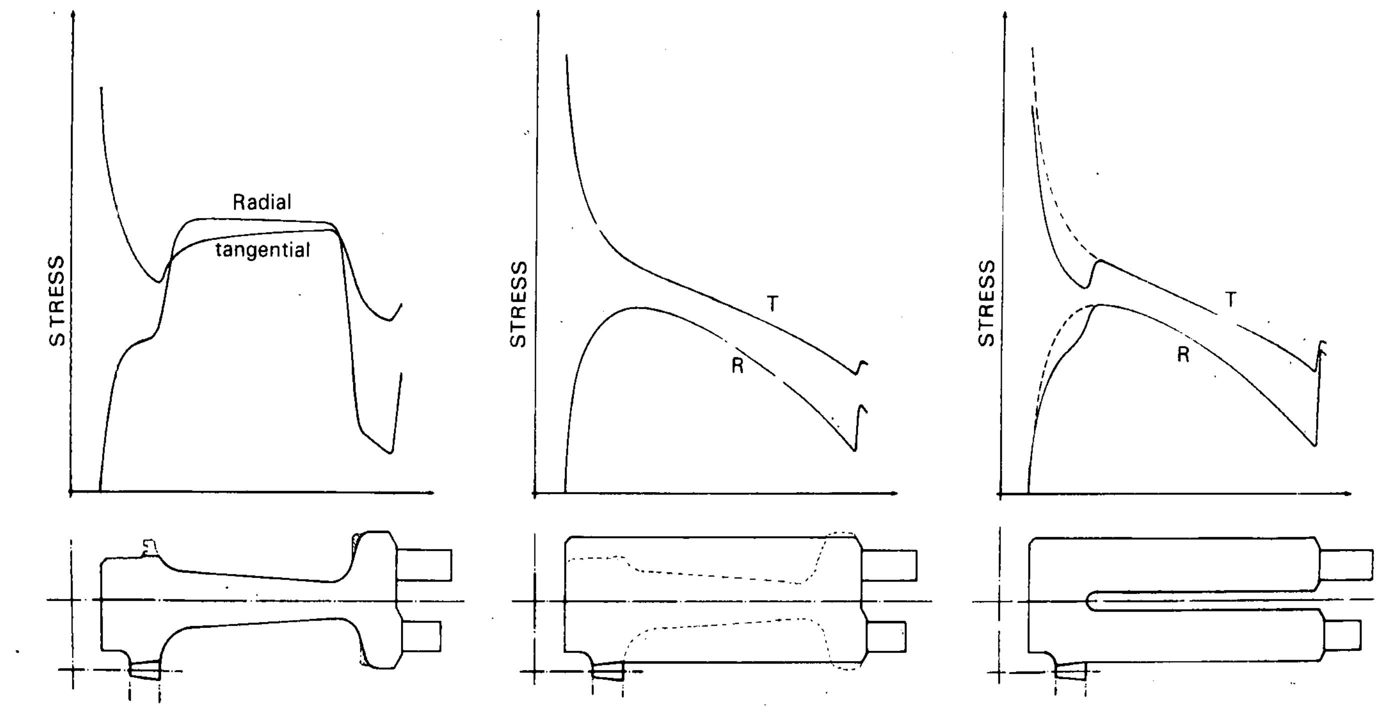
Secondly, the design of the turbine rotor must be such that the blade attachment is firmly supported, the maximum stress is not excessive and the rotor weight is such that it does not cause excessive bending of the pinion shaft and hence a low first critical speed.

The profiled rotor satisfies all these criteria.

The robust rim provides ample support for the blades, the single profiled web is simpler and lighter than the twin disc design and utilises the material properties by having as far as possible a constant stress profile. The reduction in mass results in a first critical speed well in excess of the running speed without resorting to a disproportionately stiff pinion shaft. Thus a low running speed is not panacea for turbine design, while a high running speed does not court disaster if the overall and detail design of the unit has been carefully carried out.

The overhung rotor allows simple maintenance, only the exhaust casing needs to be removed from the unit to gain full access. The hirth coupling removes the need for shrink fits and keys with their attendant stresses and stress raisers. Finally the small light rotor results in a more compact unit.

COMPARATIVE TURBINE ROTOR DESIGNS



W P L. PROFILED ROTOR 71,84 lb/32,59 kg SOLID ROTOR 123,42 lb/55,98 kg TWIN ROTOR 101,71 lb/46,13 kg

Figure 2:

Therefore when a turbine manufacturer quotes running speeds the form of turbine rotor design should be borne in mind. We will quote running speeds up to 11 000 rpm for 0,61 metres diameter rotors in the knowledge that the maximum stress levels are such that the rotor could be started every day for 500 years or more and still not fail from fatigue cycling. The reduction gearing is machined, from solid integral gear forgings in the pinion shaft and from shrunk on forged rings on the main gear. The gears are supplied either as through hardened or nitrided depending upon loading. When nitrided the gears are treated in batches together with a standard test piece which is subsequently sectioned to ensure the correct depth of nitriding has been achieved. Such precautions ensure that the turbine design is robust and will have a long life.

As previously indicated the design of the turbine does not include auxiliary gearing for driving a governor. The control is electronically based using the sensed rotation speed of the turbine shaft as its input. The increased automation on board ships culminating in the unmanned engine room, required suppliers of equipment to provide controls that could be latched into a computer based system. The AET turbine was therefore designed with fully electronic controls suitable for operation by manual push buttons or directly from a computer or other similar device. The turbine speed is sensed by a probe positioned between the pinion gear and the first bearing on the shaft. This is the most desirable position, since it is most unlikely that a mechanical failure in the turbine gearing would render it inoperative.

The turbine speed sensed by the magnetic probe as a pulse wave is fed into the control module. In this the pulse signal is passed to:

(a) a discrete frequency filter circuit that produces a stable output until the input frequency rises above a set level when the output of the circuit diminishes sharply. This drop in output is used to trip the turbine through a relay if the speed exceeds the set level.

and

(b) a pulse counter, which converts the signal into a DC voltage which is then compared with a reference voltage which represents the desired speed. The comparator output becomes the control signal to the electrohydraulic actuator on the steam control valve, the action being to regulate the steam flow to the turbine so that the speed is maintained at the desired level regardless of the power output from the turbine.

In the control and protection modules all the circuitry and components are on printed circuit boards for easy access, and are of simple robust construction. Before the controls were fitted on the first installation they underwent the tests required for "Type Approval of Control and Electrical Equipment" laid down by Lloyds Register. This included:-

(a) *Power Supply:*

Satisfactory operation during voltage and frequency variations and transients.

(b) *Vibration:*

Resonance check, and vibration at resonance or specified period.

(c) *Humidity:*

Satisfactory operation to be confirmed following prolonged humidity cycling.

(d) *Dry Heat Test:*

Satisfactory operation to be confirmed following prolonged exposure to dry heat.

(e) *Drip Proof Test:*

Tilted in two planes under prescribed conditions.

Thus it will be seen that the electronic controls have been stringently tested. Since the first units some 200 have been installed in ships with voyage times varying from 3 months to 3 days so that the turbines and their controls have had considerable testing in the very aggressive Merchant Marine environment all over the world.

Applications for Turbines in the Sugar Industry

Because of the requirement for heating in the factory of a sugar mill for the reduction of the juice into crystallised sugar and molasses it is advantageous for a high proportion of the prime movers in the plant to be turbines so that there is adequate low pressure steam for the factory.

Turbines have been used for driving the following plant,

(a) Cane knives.
(b) Shredders.
(c) Cane mills.
(d) Fans.
(e) Pumps.
(f) Turbo-generators.

With the advent of diffusion plants the prime mover for the bed can be added to the list.

Turbines are very flexible prime movers being capable of speed control over a wide range. By varying the number of nozzles in consultation with the manufacturer, powers can be changed, or different steam conditions from that originally envisaged can be handled. Further they fit in well with the high efficiency total energy concept of the sugar mill.

Operating Conditions

Turbines have to be tested for safety under all operating conditions. Broadly for cane mills there are four power conditions to be considered:

(a) *Uncoupled light running:*

When a turbine is installed it has to be run up and controlled over its whole operating speed range to enable the testing of all trip functions, overspeed, high exhaust, back pressure etc. This functional testing is carried out before the turbine is coupled to the reduction gearing to satisfy the engineers that the unit is safe. In this condition the power required to drive the turbine is very small compared with the design power. The control system and hence the control valve has to modulate the small steam flow to the turbine within close limits. A small increase in steam flow will cause a large increase in speed and so the increase in area to flow in the steam valve for a given change in signal must be very small.

(b) *Coupled light running:*

Once the above tests have been completed the turbine is coupled to the reduction gearing and mill. The reduction from turbine rotor to mill is of the order of 3 000 to 1 or greater with gear inertias and back lash to be dealt with by the control system. Here again the power required is relatively small and the controls have to accelerate the gear train and mill to the required speed and hold this with no stabilizing load in the mill to stop over-run once the desired speed has been obtained. Once again therefore the control system, and hence the control valve, has to modulate the steam flow accurately about a relatively small flow. However, since the power demand is higher than in the uncoupled condition, the increase in area to flow in the steam valve for the same change in signal in "a" above will be a little larger.

(c) *Coupled running:*

Here the control system has to prove that it will maintain the turbine speed and hence the mill through-put at a set level regardless of the rate of cane input and quality. If the cane through-put increases to such an extent that the mill may overflow then the controls must respond to a speed increase signal, raise the turbine speed and hold it steady at the new set level. Here the power demanded of the turbine is high and the load fluctuations are large therefore for the same signal change considered in "a" and "b" above the change in area to flow in the control valve must be large.

(d) *Starting a stalled mill:*

This will be dealt with later.

Two factors affecting the required responsiveness of the control system are:

1. The quantity of imbibition water used in the extraction process.
2. The position of the mill in the mill train.

Before dealing with the results that have led to the above conclusions, let us examine the result of the rough analysis in steps "a", "b" and "c" above and then relate this to the present commissioning experience in Weir Pumps.

Considering control conditions "a", "b" and "c" above it will be apparent that as the load on the turbine increases and the steam valve has to open further, the rate of change of flow area has to increase. Alternatively as the valve lift increases the rate of increase of flow area also increases. Therefore the valve characteristic required is similar to that known as the equal percentage form.

This agrees with our experience on the type of valve required for the control of pump drivers. However, where the systems differ is in their form of energy absorption. The pump has a predictable characteristic where, given the pump characteristic the horsepower absorbed is proportional to the cube of the speed ($HP \propto N^3$). This is because the system resistance against which a pump operates has the well known square law relationship; head is proportional to the square of flow.

In the cane mill on the other hand the aim is for as constant a crushing pressure as possible, so that ideally $HP \propto N$. However, the cane flow and quality varies in a random fashion especially at low load when the cane has no chance to consolidate in the chute prior to entering the feed rolls. This results in an erratic rate of power demand. The result of this is the requirement for a much faster speed of response in the control system than is required for the control of a pump driver.

Experience with the AET in the sugar industry

Huletts Sugar Limited were the first purchasers of these units for use in the Darnall Mill. The first unit was a 1902 kW (2 500 hp) 18/21 size unit to drive a new shredder. The unit was installed early in 1976 and is now into its third crushing season. The following "off crop" three 16/16 AET's rated at 634kW (850 hp) were installed on mills 3, 5 and 7 and at the beginning of this year a further three 16/16 units were installed on mills 2, 4 and 6 thus completing up-rating of the mill train at this plant.

The shredder is in effect an 18 300 kg flywheel so that as the load on the machine varies from instant to instant the inertia effect tends to iron out load fluctuations. In spite of this, the control system as initially installed was modified to increase the response rate by a factor of two to obtain more acceptable results.

In the case of the mill no such flywheel effect is present and therefore there is no smoothing out of speed fluctuations due to load changes. The control system therefore had to be faster than on the shredder.

Early tests on units 3, 5 and 7 established that, contrary to what we understand has been accepted both in theory and in practice, it is not correct to assume that it is always at the first mill that the difficulties in speed regulation are greatest. It has also been assumed that the control of the subsequent mills is either progressively easier or all mills have similar characteristics. The tests clearly showed that as one progressed from the first mill to the last, the control response speed required to maintain acceptable stability of the turbine speed increased quite considerably.

It is postulated that this is due to change in the size and nature of the cane fibres as they are ground or shredded down by the passage through the mills, also the differing moisture content at each mill due to the progressive back wash to number 2 mill.

As has been stated by Hugot[1] "the governor is the most critical unit in the turbine" and "must be of very first-class type". This is undoubtedly true when one considers the constantly varying load in a cane mill. Figures 3 and 4 illustrate the control obtained on the last mill in the train with two different control response rates, the first being equal rate opening and closing, the second being twice the speed opening and five times the speed closing of the first system. The three graphs show (top), turbine nozzle box pressure in KPa (psig) (centre), the turbines output shaft speed rpm and (bottom) the actuator signal in volts D.C. At the bottom of the charts there is a ten second marker to indicate relative chart-speeds.

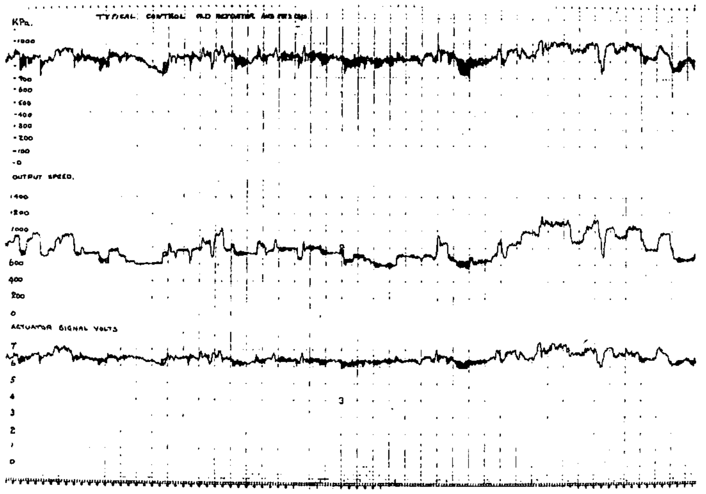


Figure 3:

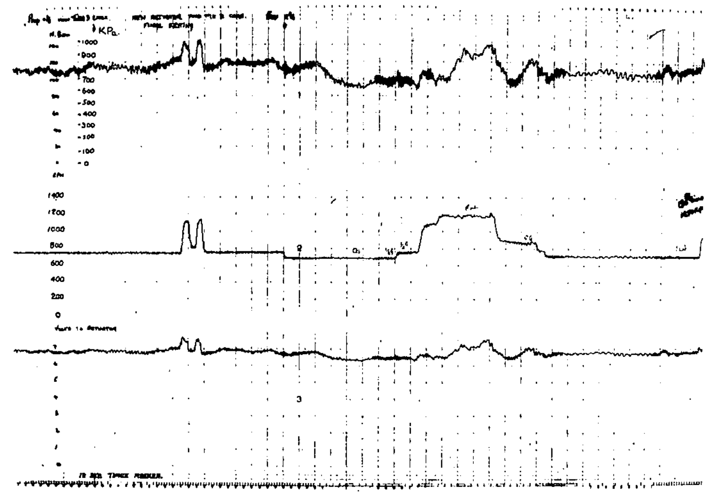


Figure 4:

The last mill in a train is very important for two reasons:

(a) it removes the last commercially viable recoverable quantity of sucrose from the cane.

(b) it squeezes the bagasse to render it as dry as possible so that it goes on to the store or the boilers in the best condition for free flowing in the conveyors and feed chutes and also for combustion.

Thus it is vital that the crushing in this mill be optimised as far as setting, cane flow and packing in the chute is concerned and finally a steady rate of crushing must be maintained consistent with maintaining the correct inlet level. The graphs of speed in Figures 3 and 4 are not startlingly different. However the difference in response of the controls is shown more dramatically if we examine their respective performances during the starting cycle of the mill train.

Imbibition is used to increase the extraction efficiency of a mill train. While this has been used for some time now, we do not believe the effect of this on the dynamics of the mill has been investigated.

When the last mill in a train is started it receives cane/bagasse with a relatively low moisture content and the mill has to crush this "dry" cane until the imbition water is available, once the steam/feed water system has stabilised.

When recorded testing began on the turbines no note was taken of the presence or quantity of imbition water being added to the cane entering the last mill. However, when a start cycle was being recorded the control shown on Fig. 3 could not be repeated until suddenly the speed fluctuations diminished considerably as shown in Fig. 5. It was found that this change coincided with the turning on of the imbibition water. This was later checked and the same change was noted about 1,5 minutes after the actual turning on of the imbibition water. It was clear therefore that the moisture content of the cane in a mill had a significant effect on the dynamic characteristics of the mill. Having established that this change in mill dynamics occurs during startup, it was obvious that the control system would have to be able to control the turbine speed within acceptable limits during this starting transient condition.

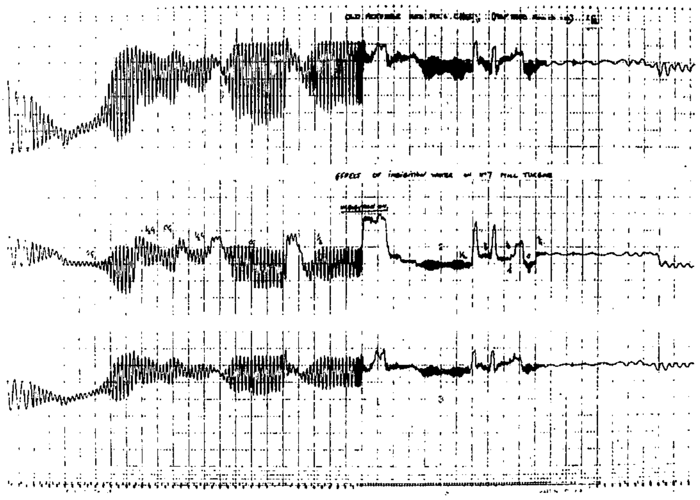


Figure 5:

Figures 6 and 7 illustrate the effect of control response on the stability of turbine speed using the control settings corresponding to Figures 3 and 4 respectively. The more rapid response of the second control system clearly controls the speed more accurately under the fluctuating load conditions and this was confirmed by further tests. With the faster response controls there was still a slight change in control when the imbibition water was turned on but this was not recorded because the basic control function had been solved.

Under steady load and with imbibition the control was within ± 10 rpm at speeds up to 1 400 rpm, the duty speed of the turbine. Figure 4 shows the standard obtained.

From an analysis of the behaviour of the turbine under no load (uncoupled), light load (coupled) and full load, the correct

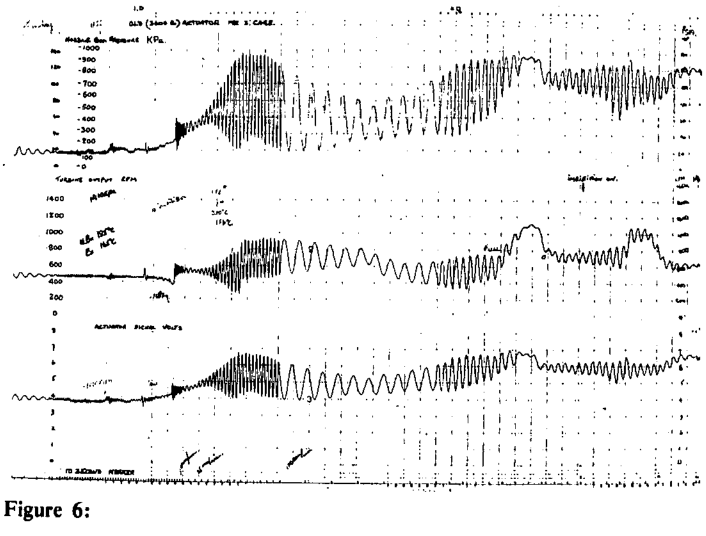


Figure 6:

profile for the control valve was designed and the speed of response required from the controls, primarily the electro-hydraulic actuator, was found. When these were combined and the proportional band setting in the electronic controls correctly adjusted satisfactory control was obtained under all cane throughput loadings from zero to more than 330 tons per hour and for steam pressures from 75% to 110% of design.

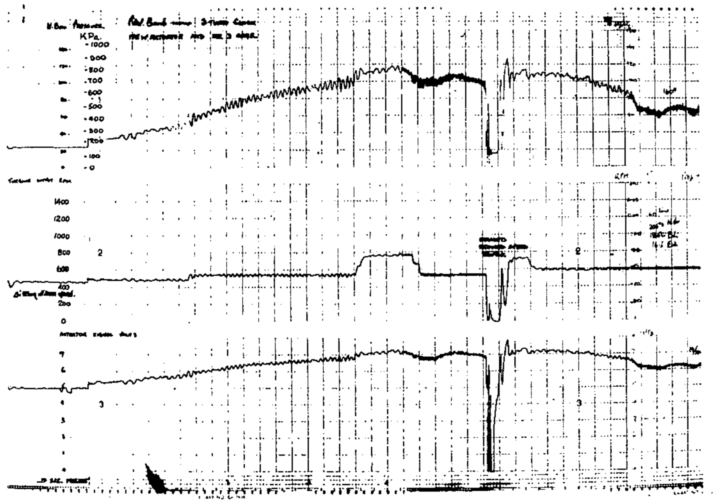


Figure 7:

If the practical day to day problem of running a mill is considered, two vital quantities are tonnage crushed and extraction. Further, the steam pressure in the mill range is not always constant. There may be many reasons for this but the effect is that the turbine will no doubt be operated at speeds below the design speed and at various steam pressures.

What is the effect of this? Should the mill operators worry about it?

It is highly unlikely that any of the mill shift engineers will consider the above questions so long as the mill is crushing to capacity and extraction is good.

If we consider the effect of operating the turbine at a series of given nozzle box pressures we can plot a family of curves similar to those shown in Figure 8 or Figure 9. From this it can be seen that under certain operating conditions of reduced speed and nozzle box pressure the torque transmitted by the turbine is greater than that at full rate power and speed. The turbine can develop a "stall torque" some 70% greater than the rated torque.

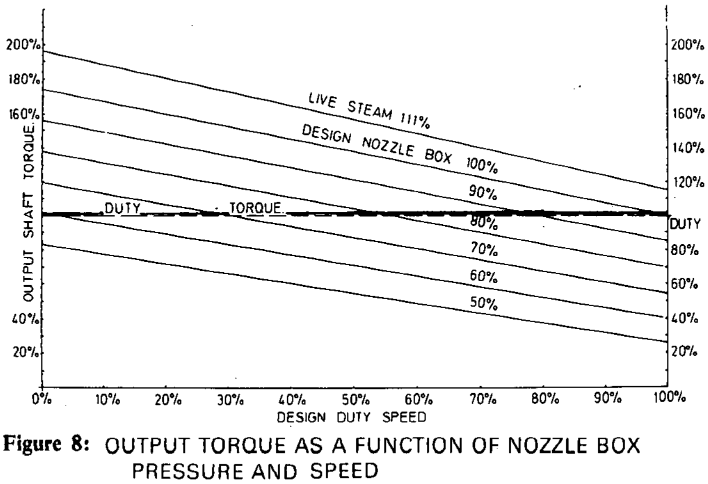


Figure 8: OUTPUT TORQUE AS A FUNCTION OF NOZZLE BOX PRESSURE AND SPEED

If we consider the case raised earlier of starting a stalled mill, it is a boon to the engineer to be able to restart the mill without removing the cane. However there is the other side of this to be considered; that of overloading gearing, bearings etc.

As steam turbine designers we submit that this torque capability should be considered when rating associated plant because in all probability the turbine *will* operate for an appreciable part of its life in this high torque zone and the associated plant may not be designed with the same safety factors used by the turbine designer.

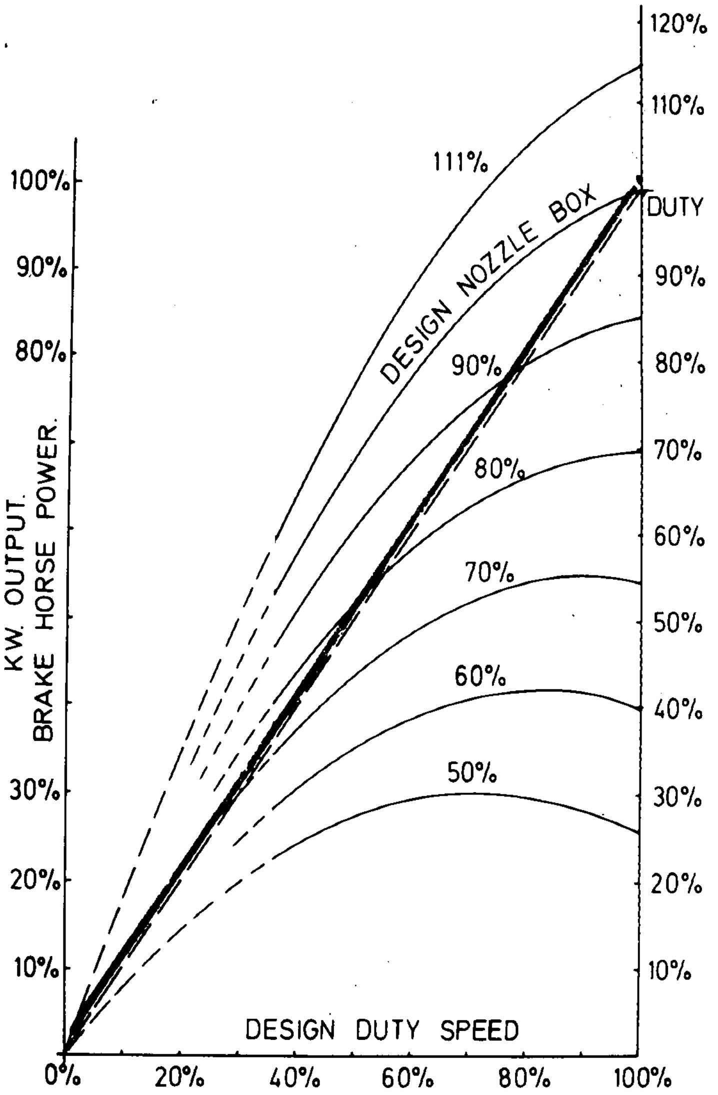


Figure 9:

It is important to note that despite its deceptively small size the modern steam turbine is a very powerful prime mover and should be treated with respect by the plant designer, the contract engineer and the mill engineer.

Before concluding this section, there may be those who would be interested in the test instrumentation used to obtain the results presented in the graphs. The recorder used was a three channel separate chart recorder with both a 10 sec or 10 min automatic marker, also an event marker, capable of high chart speeds. The nozzle box pressure was sensed by a transducer and fed as a voltage signal into the recorder. The signal to the electrohydraulic actuator was 0-8 volts DC and the tacho signal was picked off the controls as a DC potential difference and both fed into the recorder. Some suppression of hum and high frequency transients had to be employed to provide the clear recordings obtained. Although there may be some who would not consider a sugar mill an ideal situation for the use of such a sophisticated instrument, with care it survived the "ordeal" in perfect condition.

Milling in the Future

We have been led to understand that there is a trend away from extraction based on straight milling of cane in South Africa, the preference being for the diffusion process. However there are several positive results to come out of the tests that have been described.

1. Existing mill trains could be up-rated in a similar manner to that at Darnall with increased output and higher extraction rates being obtained.
2. As was indicated before the AET controls are suited to receiving control signals (0-10 volts DC) from a computer or other device and tests have shown it possible to couple a chute level sensor to the controls to maintain optimum cane level in the chute regardless of the crushing rate, i.e. automatic mill control.
3. By applying the above, the expenditure required to install a new diffusion plant could be postponed for some appreciable time.
4. For diffusion plants there is still the need for good preparation of the cane prior to the diffuser and efficient dewatering of the bagasse after. For these, accurate control is a prerequisite, especially in the case of the dewatering mills where the moisture content of the final bagasse should be as low as possible.
5. Using the full potential of the AET with its capability for automatic control and protection it is possible to convert existing plant to fully automatic control from a master panel supervised by one engineer, or even without him!

Reliability

Given the operating experience gained over many years with the former turbines, the AET units which are based on the same fundamental principles will we believe prove to be serviceable units for the sugar industry.

Acknowledgements

The commissioning of the AET Turbine at Darnall Mill has given Weir Pumps a lot of valuable experience. We would like therefore on their behalf to thank the Directors and Engineers of Huletts Sugar Limited for their co-operation in what we believe has been a mutually enlightening exercise and also the Department of Mechanical Engineering of Natal University for the loan of the recorder on which the traces presented were made.

Finally we would thank the Board of Weir Pumps Limited for permission to present this paper.

REFERENCES

1. Hugot E (1972). Handbook of Cane Sugar Engineering 2nd Ed. Elsevier, Amsterdam.

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