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Field Observations of Transient Servopressures in Kaplan Turbines

Transient load rejection data obtained from and applied to Kaplan turbines are presented. The dynamic response of the system was investigated and stabilized after blade servopressure analyses. The interrelationship between gate position, blade position, blade servopressure, draft-tube pressure, and speed is shown for Kaplan turbines and propeller turbines for different types of load rejections.

Introduction

The information in this paper was obtained from and applied to Kaplan turbines to improve their transient dynamic stability following load rejection. Also, the transient behavior has been improved on fixed-blade propeller-type turbines by applying information found in the servopressures of a similar Kaplan turbine.[1] The turbines selected for this field research were well suited to measurement of the transient-state load conditions and responses, for they had roller bearing supports at the blade journal. Both the roller bearing and the sleeve bearing-type journals have been designed; however, with the roller bearing system, the effect of bearing friction on the servo-oil pressure system is minimized, and the system must only overcome the hydraulic forces on the blades. In addition to overcoming the hydraulic moment of the blades, the servo-oil pressure must also be able to retain the blades in their position when hydroelastic coupling and centrifugal force are applied to the unit.

The findings are of interest in three areas: (*a*) They display graphically the magnitude and direction of the hydraulic forces; (*b*) they display the effects on stability at shutdown; and (*c*) they provide field data useful in engineering analysis and design.

Apparatus

The Kaplan units stabilized by the procedure analyzed in this paper had four blades and a semispiral case with minimum length of intake. Other data have been obtained and analyzed from five and six-bladed units by a similar data collection procedure. These yielded similar results and conclusions. In each case, the blades were supported identically and had similar blade and servosystems. The range of net heads did, however, vary between 24 and 70 ft.

Instrumentation

Instrumentation used in the data acquisition measured blade and gate positions, speed of the unit, blade servopressures, and draft-tube pressures below the runner at the mandoor. The pressures in all cases were measured using previously calibrated strain-gage pressure transducers of the diaphragm type. Both the blade and gate positions were measured by attaching a rotational potentiometer to the appropriate restoring arm mechanisms of the governor. The speed of the unit was determined by a tachometer generator which gave instantaneous rpm.

Each of the data acquisition components was recorded on an eight-channel strip-chart device. In this way, the dynamic variations appeared simultaneously and could be readily analyzed. Examples of these are seen in the figures. An independent time-pulse was recorded on the strip-chart with each test.

Test Procedure

Two types of load rejections were made, one to speed-no-load and one to complete shutdown. Even though the less frequent type of rejection will be to speed-no-load, this condition resulted in more severe instability prior to adjustment. Feedback, due to sudden reduction of load, caused this behavior and it is prolonged by the gate position speed dependency. Thus a higher degree of adjustment was required for a Kaplan turbine to reach a stable state of speed-no-load than to reach a condition of complete shutdown.

The testing requires that most of the effort be allocated to: (*a*) Setting up the instruments and apparatus, and (*b*) load rejection, analysis, and adjustment. The time required for the data collection phases of either type of rejection was insignificant in the overall time required to run the test. The technique was identical, with the exception of the appropriate circuit tripped, to cause either type of rejection. A list of the steps taken for a single load-rejection test is as follows:

1 Stabilize the unit on the desired load.
2 Record headwater and tailwater elevation.
3 Record steady-state output data onto the strip-chart.
4 Reject load by tripping circuit breaker.
5 Monitor recorded results to assure that shutdown will not be required by manual means.
6 Continue recording until the unit has stabilized.

Analysis

The figures shown are copies of the strip-charts to which scale identifications have been added and magnitudes altered for clarity. Blade position and gate position are presented as percent of full open. Pressures are represented for the servo-oil system in psi, while those in the draft tube are given in feet of water. Blade servopressure to open signifies a hydraulic closing moment of the blades and vice versa. A steady-state condition is reported between the times of -5 sec and load rejection at 0 sec. Transient responses are shown along the plus time axis.

A sequence of load-rejection levels, as outlined subsequently, was followed. This began by adjusting the unit to one quarter of its rated output and was necessary only to check the dynamic behavior of the turbine governing system. Fig. 1 shows the results of rejecting one-quarter load to speed-no-load. Very little fluctuation appeared in the blade servosystem as, at this point in operation, the blades are in flat position and independent of the gate position. Therefore, instability should be a minimum due to a load rejection. Shutdown was smooth and without gate oscillations due to overspeed. The recovery to speed-no-load was generally as expected and the unit stabilized without assistance from the operator.

[1] A literature search of American and foreign literature has revealed little published work in either of these areas. *Escher Wyss News*, vol. 36, 1963, discusses similar measurements taken during overspeed tests; however, no load rejection data were given or discussed.

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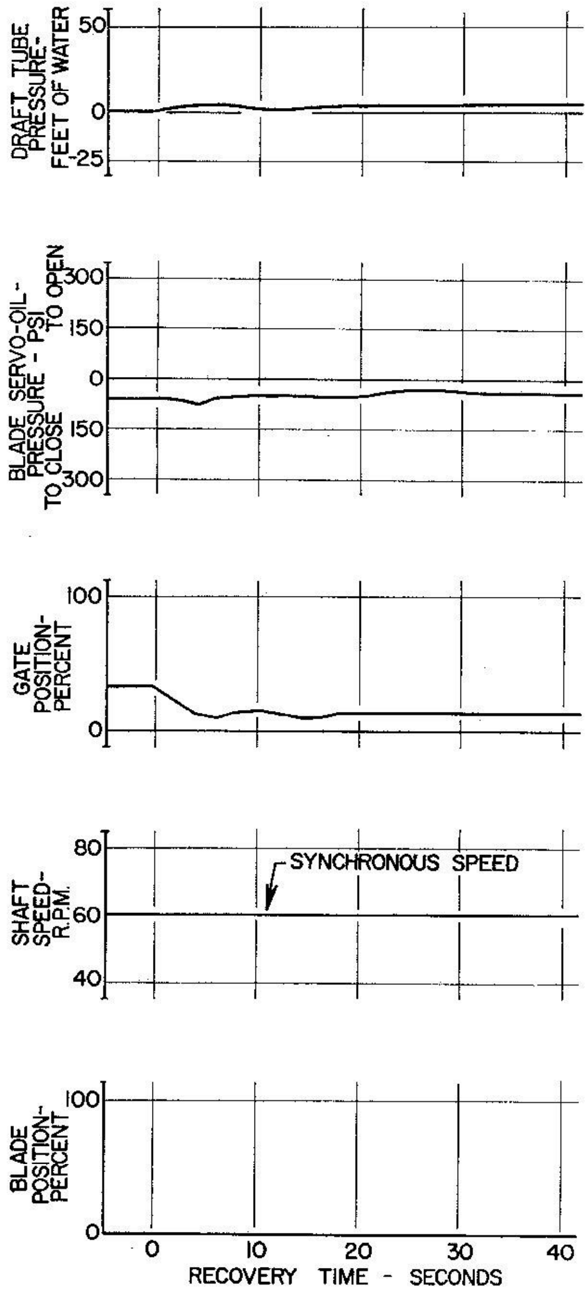

Fig. 1

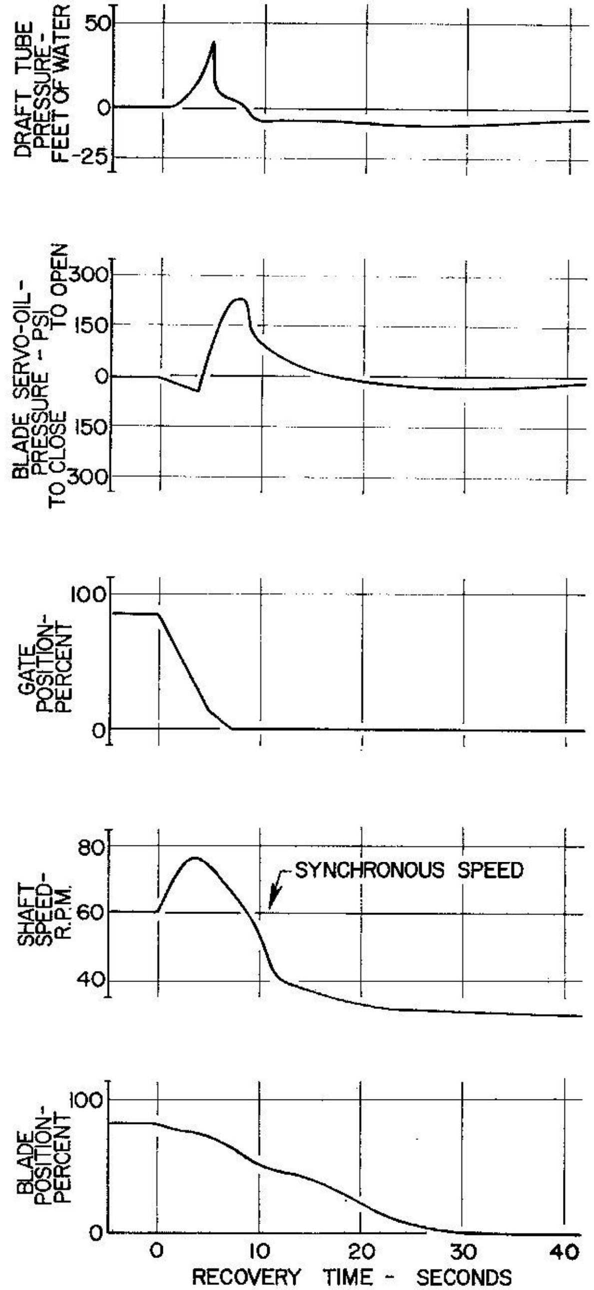

Fig. 2

With the system operating correctly when one-quarter load was rejected, half-load was then examined. During operation in this range, a coupling should be noted between the gates and blades if the blades have been opened by the cam. Generally, adjustment in this load range will also be unnecessary, and the three-quarter rejection will be the first to require adjustment. It is at the three quarters of full load where transient responses were generally first measured in the servo-oil pressure and in the draft tube. Judgment dictates that the conservative approach, measuring quarter and half-load rejections prior to attacking those which need adjustment, must be taken, although increasing the level of load rejections in smaller increments becomes necessary when the transient response is particularly ill-behaved. Descriptions of the specific changes follow.

Analysis of the servo-oil pressure was employed to adjust a Kaplan unit and to adjust a propeller unit. Both analyses used the same technique, but the second of these eliminated the study of blade position and studied only the improvement of the stability of the hydraulic moment on the fixed-blade unit.

First, a comparison of load rejection to speed-no-load and load rejection to complete shutdown from full load is discussed. Second, details of the behavior of rejection to speed-no-load are discussed. Finally, analysis to establish the best stability point of a propeller unit is outlined.

Comparison of Rejection to Speed-No-Load and Rejection to Complete Shutdown

A rejection of load to speed-no-load, while the generator was producing one quarter of its rated output, is shown in Fig. 1. It is not indicative of responses to be expected when greater percentages of the rated load are rejected. Fig. 2 is typical of the transient response to a rated load rejection to complete shutdown and is, therefore, discussed fully. The comments which follow discuss the response of each of these parameters as a function of time.

The draft-tube pressure plot indicates a rapid surge reducing to a negative value and remaining as such until the condition of speed-no-load is reached. Although the head-cover air valves

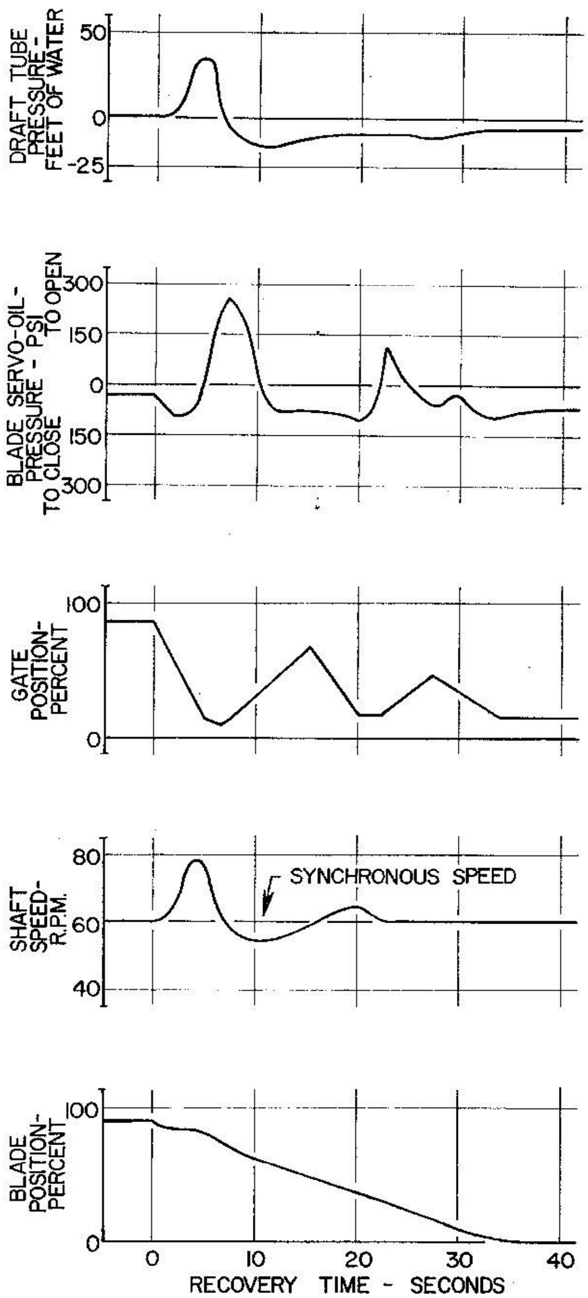

Fig. 3

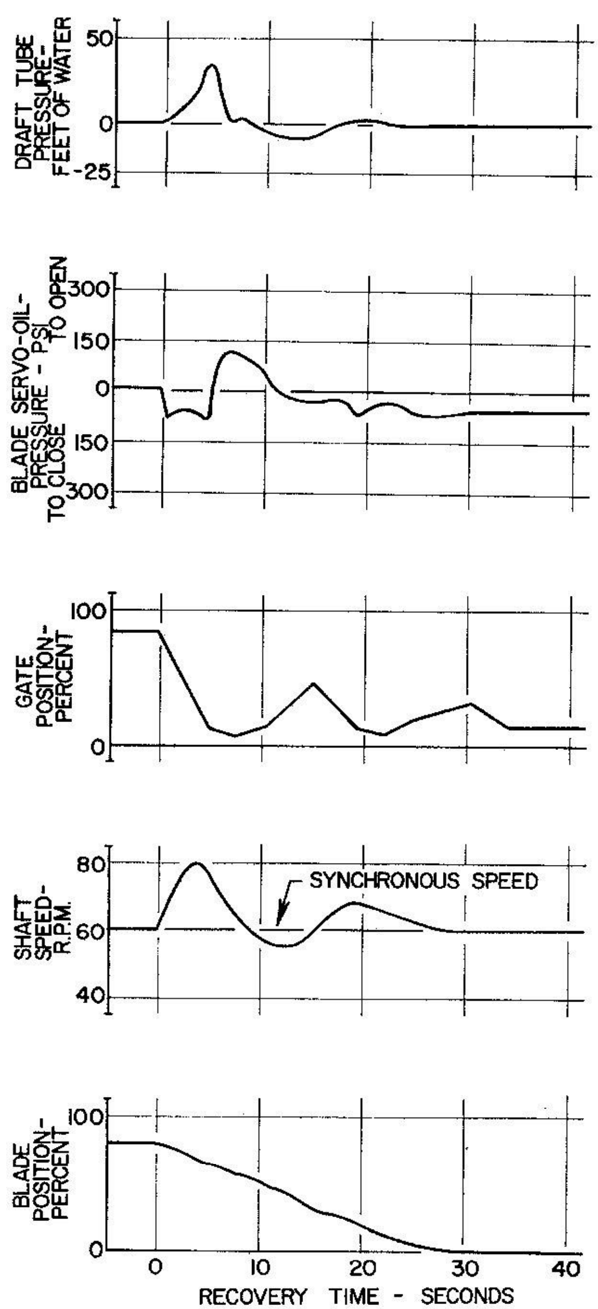

Fig. 4

were functioning properly and admitted air to the runner chamber, their action is not recorded. This pressure rise resulted from speed rise of the turbine when the electrical load was dropped from the generator. Speed rise, in conjunction with an abnormal gate opening, apparently permitted a large quantity of water to pass through the turbine. The differential blade servo-oil pressure plot shows that it was well-behaved until time, T, equals 3.75 sec. At this time, the surge in the draft tube and the centrifugal force due to speed rise surpassed the tendency of the governor to close the turbine blades and tried to force a more rapid blade closure than the governor setting would permit. The oil on the opening side of the servopiston was forced back through the governor and an increased pressure resulted. This blade servosystem, which was designed for 300 psi to open and 300 psi to close, reaches a maximum value of 225 psi to open at 7.25 sec, or approximately 3 sec after the draft-tube pressure surge had begun to diminish. The blade servo-oil pressure surge then began to decrease and was well-behaved until the turbine reached the condition of complete shutdown. The gate position of load rejection being discussed here indicates an initial setting of 85 percent of full gate. Gate closing was at a predetermined uniform rate until 13 percent of the servomotor stroke remained. At this time, a cushioning valve throttled the oil flow from the servomotor piston and reduced the rate of gate closure to another predetermined value. Prior to the beginning of tests on both this Kaplan unit and the propeller unit discussed later, the gate cushioning times had been set at 2 sec. After rejection, the gates progressively closed and remained in that position. Following the initial rise, the speed decreased until it reached a value of 0 rpm. The zero speed is not shown on the chart for, below the speed of 30 rpm, the brakes were applied to the unit. The position of the blades, once initial closure began, continued at a relative linear rate until complete closure was reached.

The conditions prior to rejecting the load and collecting the data for Fig. 3 were identical to those for Fig. 2. Fig. 3 is, however, rejection to speed-no-load condition. The command to close the gates was given by the governor as a function of overspeed, with the purpose being to maintain the speed at 60 rpm, rather than to stop the unit as was the case for load rejection to complete shutdown. For this reason, the gates were then permitted to seek the required position. In so doing, additional pressure surges were produced in the draft tube which reflected in the blade servo-oil pressure, blade position, and speed. Two complete gate position cycles were exhibited before the stable condition was reached. A piston design pressure of 40 psi was necessary to hold the blades in the closed position at speed-no-load. It was apparent that the transient period to speed-no-load was less stable than the transient period to complete shutdown, thus indicating a need for finer adjustment to the servo-oil system.

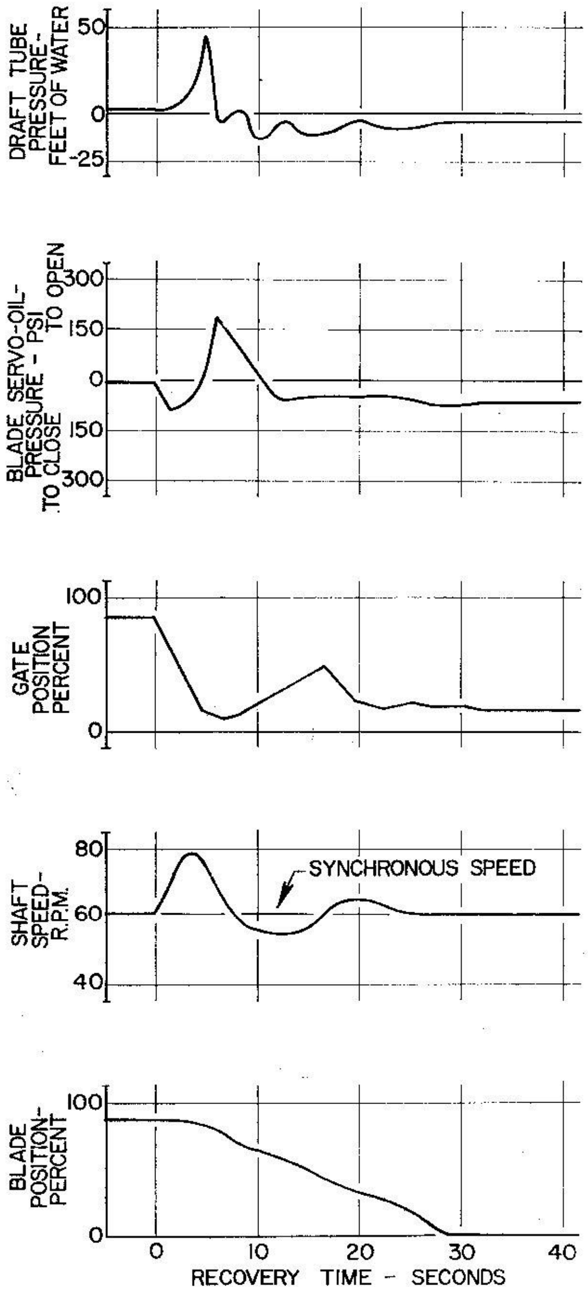

Fig. 5

This detailed discussion of Figs. 2 and 3 should draw attention to the magnitude of the blade pressure surges and speed rise during the recovery period. Attention should be given to the gate closure time, the gate cushioning time, and the correlation between gate position and speed for stability.

Fig. 4 shows the results of rejecting the same previous load to the speed-no-load condition. The gate cushioning time was increased from 2 to 6 sec. As a result, the servo-oil pressure was reduced 45 percent—from 240 psi maximum to 130 psi maximum. This represents a significant reduction in blade moment, while the draft-tube surge remained at approximately the same magnitude. All other adjustments reported on the prior test remained unchanged. By increasing the gate cushioning time, the time to reach the condition of speed-no-load was substantially reduced. When the gate opening period from "cushion" to full open was increased from 12 to 20 sec, the increased stability shown in Fig. 5 resulted. Here stability was attained with only one gate cycle in about 25 sec. The gate cushioning time, 6 sec to close the gates from cushion to 0 percent, remained unchanged. The number of gate cycles was reduced from two to one, but the blade servopressure increased slightly. Prior to arriving at the cushioning period of 6 sec, other tests were made using longer and shorter times which were less beneficial to the dynamic performance during load rejection.

Table 1 summarizes the data from five selected indicative tests and shows that the maximum speed rise reaches a more favorable condition with Fig. 5 than when using the values for gate cushioning and gate opening times shown in Fig. 4. The maximum blade servo-oil pressure for this condition is 180 psi, which is 50 psi less than for Fig. 2 and well below the design capacity. For these reasons, this unit, as well as the other Kaplan units in the power house, were set at the aforementioned gate cushioning and gate opening times. The most favorable combination of blade servo-oil pressure and speed rises occurred with these settings.

Stabilizing of a Fixed-Blade Unit

The introduction to this section stated that a propeller unit identical to the Kaplan unit was also stabilized. Experiments were conducted by setting the blades of the unit at 80 percent of full open and repeating the tests to simulate operation of a fixed-blade propeller unit. The measurements were taken on the Kaplan and the results transferred to the adjacent propeller unit. The assumption was made that these identical units would behave similarly if the Kaplan blades were set at the fixed-blade position of the propeller unit and the blade servosystem made to respond rather than respond and control. The blade position of the turbine was then independent of the gate position, but the gates remained under control of the governor.

This independence was introduced by removing the cam, lifting the follower, and locking it at 80 percent of full blade stroke. With the absence of a dependent gate-blade relationship, the blade servomotor pressure counteracted the hydraulic blade moment but did not position the blades.

Fig. 6 shows each of the characteristics when the unit was

Table 1 Summary of Kaplan data

Fig.	Rejection to	Load, percent	Speed rise, percent	Maximum transient blade servo-oil pressure, psi	Gate cushioning time to close	Gate time to open from cushion to 100 percent	Number gate cycles
1	S-N-L	25	2	80	2	12	½
2	Shutdown	100	28	230	2	12	1
3	S-N-L	100	30	240	2	12	2
4	S-N-L	100	33	130	6	12	2
5	S-N-L	100	28	180	6	20	1

rejected from full-load to speed-no-load and the blades fixed as before. The cushioning time for the gates, during the run, was 2 sec, and the opening time from cushion to full gate was 12 sec. These settings correspond to those at which the fixed-blade unit was being operated. Table 2 compares the settings and results of the fixed-blade tests. Observations of the oscillograph charts indicate that the gates were overcorrecting and that the transient state would have continued through many more cycles than those recorded. Failure of the gate swing, at the end of 140 sec, to converge to a steady state required manual operation for recovery. Again, the first adjustment for stabilizing the turbine was to increase the cushioning time from 2 to 6 sec. The results are indicated in Fig. 7. This adjustment resulted in the turbine reaching a steady state 46 sec after rejecting load. In addition to now having the turbine controlled by the governor, the blade servo-oil pressure was reduced 14 percent, and the speed rise was reduced by 5 percent.

When the period to open the gates from cushion to full gate was increased from 12 sec, the load-rejection characteristics shown in Fig. 8 resulted. For this condition, the magnitude of the blade servo-oil pressure and the speed rise remained nearly unchanged. However, the magnitude of the draft-tube pressure surge was

Fig. 6

Table 2 Summary of simulated propeller data

Fig.	Rejection to	Load, percent	Speed rise, percent	Maximum transient blade servo-oil pressure, psi	Gate cushion-ing time to close	Gate time to open from cushion to 100 percent	Number gate cycles
6	S-N-L	100	37	315	2	12	6+
7	S-N-L	100	33	280	6	12	3
8	S-N-L	100	32	275	6	20	2

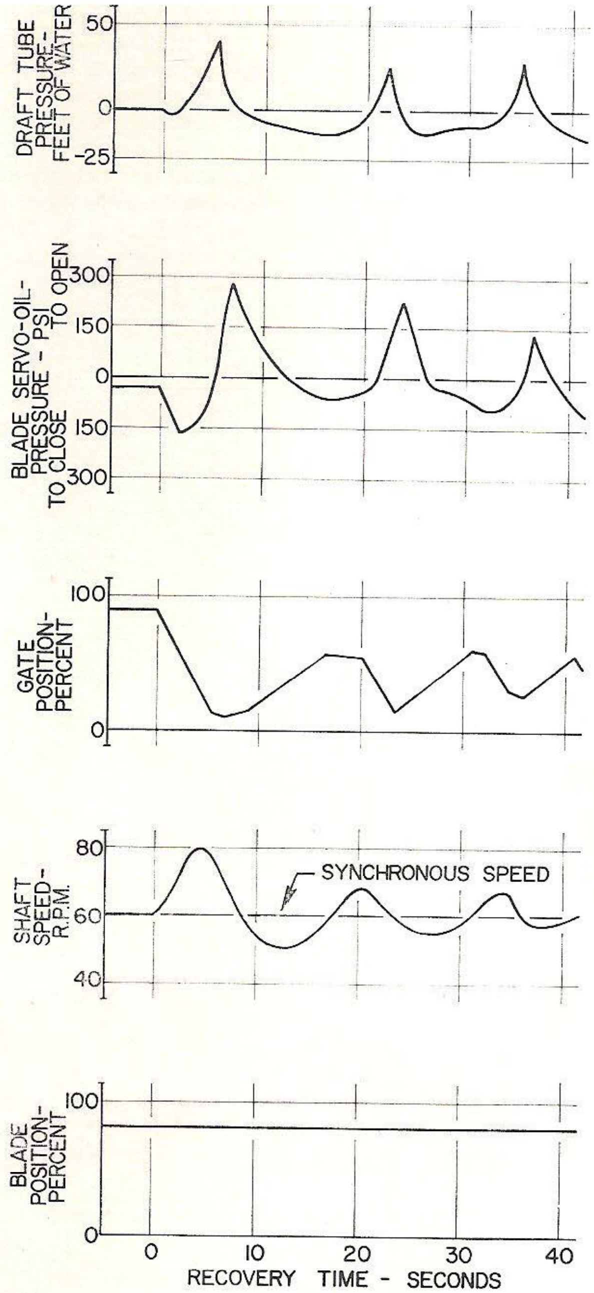

Fig. 7

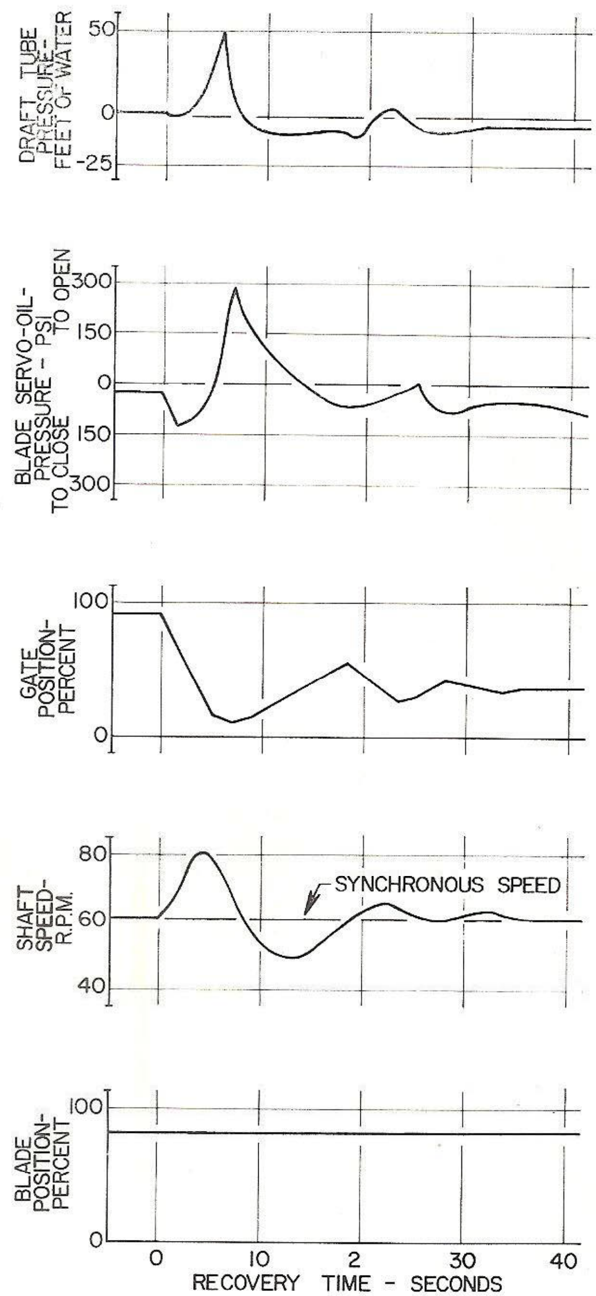

Fig. 8

reduced to approximately half of its prior value. The period of time required to bring the turbine under control was less than 2/3 of the period for a 6-sec gate cushioning time and the 12-sec gate opening time, and the unit no longer needed manual assists. Quieter operation was noticeable during the transient period following the stabilization of the unit.

Summary and Conclusions

These studies represent graphically simultaneous conditions as they occur during two modes of load rejections on a Kaplan turbine with roller bearings at the blade journals. They also show how benefits may be had by adjustment of gate timing. The benefits appear in reduced force on the mechanism and improved stability and recovery of the unit after load rejections. It is not asserted that every unit would respond alike, but it is believed that proper testing can produce similarly improved operation. For the units tested, the following conclusions are made:

1 The dynamic response during load rejection of a Kaplan turbine can be measured through proper instrumentation to the blade servomotor system.

2 An interrelationship between draft-tube pressure surge, speed rise, gate response, and differential blade servo-oil pressure during the transient behavior of a turbine has been shown to exist.

3 Load rejections to speed-no-load are more susceptible to dynamic transients than are load rejections to complete shutdown.

4 Stability of a Kaplan unit during load rejection is dependent on the gate timing during the cushioning period.

5 Stability of a Kaplan unit during load rejection is dependent on gate opening time above the cushioning range to full open but is less critical than the gate cushioning time.

6 Hydraulic moments on blades are controllable within certain limits by adjusting the gate rates without detrimental speed rise to the turbine.

7 Adjustment of the gate closing and opening times for a fixed-blade turbine indicates that these should be the same as those of a similar Kaplan unit.

DISCUSSION

P. L. Moran[2]

The authors have done a fine job in documenting the transient conditions following a load rejection sustained by propeller-type turbines, both fixed and adjustable blade types. The corrective measures recommended will certainly help to improve the load rejection characteristics of this class of machine.

As control manufacturers, the Woodward Governor Company has been aware of this problem for some 30 years, and in that time has developed and used techniques similar to those of the authors to provide satisfactory control characteristics. A good rule of thumb for predicting when unusual operation may be experienced is to note the expected speed-no-load gate opening. Any required gate opening above approximately 15 percent would indicate that some trouble might be expected. In addition to possible oscillatory response of the turbine wicket gates, in certain designs lifting of the unit off the thrust bearing has been observed.

To eliminate these two conditions, we have developed a low gate stop which prevents the normal governor action from closing the gates much below the speed-no-load opening. This device and its operation were first reported in a paper by J. D. Scoville.[3] This equipment was developed and used on small-sized units about five years earlier.

Publishing information and test data of this type can only help in acquainting all those who use turbines and control equipment of this type of the operation which can be expected and the steps required to circumvent certain undesired characteristics.

[2] Engineer, Woodward Governor Company, Rockford, Ill.

[3] J. D. Scoville, "Speed Regulation of Kaplan Turbines," Trans. ASME, vol. 63, 1941, pp. 385–394.

Authors' Closure

The authors wish to thank Mr. Moran for his valuable discussion. The solution he suggests pertains to the governor rather than the prime mover, but the net result appears to be similar.

The data given by Scoville and that included above seem to indicate that the hydraulic system, during load rejections, would respond in a similar manner. This would be independent of the method by which the gates were restricted from closing much below speed-no-load.

The conclusion drawn from both approaches is that the Kaplan turbine can be made to respond to load rejections in a more stable manner. By lowering the rates of final gate closure, using the proper selection of gate cushioning time and governor adjustments, less hydraulic disturbance and, thus, lower mechanical stresses result.