water passage. Considering the air bubbles to form a cushioning effect in the upper half of the runner, it could be possible that the source of the trouble is near the runner hub. With this in mind, reshaping of the upper half of the bucket discharge edges might serve to reduce the vibration and noise to a satisfactory level.

Cavitation damage to the bucket discharge edges has been reduced to a very minor amount on all runners with the reshaped edges. During the 1959 annual unit inspection, it was noted that a hard black scale was forming on most of the bucket edges. In Fig. 9, the Unit Operation Data show the unit service time and MWH generated since reshaping the bucket edges compared to the total unit time and MWH generated. The capacity and load factors shown give a general idea of unit load conditions since reshaping the bucket edges.

The failure of the bracing ring installed on the Whitney Dam turbine runner indicates that the bucket vibration has not been completely eliminated by reshaping the bucket discharge edges.

The return of the turbine vibration and noise at abnormally high heads above design head may indicate that a different configuration of the bucket discharge edges would be more effective for all operating conditions.

Acknowledgments

It is desired to acknowledge the co-operative attitude of the turbine manufacturers in all of the work described in this paper. Some of the methods used were advanced by the manufacturers, and procedures proposed by Corps personnel were discussed with manufacturers' engineers prior to application. The half-bullet-nosed edge was suggested by the Newport News Shipbuilding and Dry Dock Company engineers as a possible solution and is understood to have been derived from ship propeller design experience.

DISCUSSION

I. Swiecicki[1]

The author comments that the action of compressed air injection in reducing the vibration and noise caused by bucket vibration is not understood. An explanation can be found in the paper "Acoustic Method of Investigation of Cavitation in Hydraulic Turbines," by S. B. Stopsky, *Gidroturbostroenie*, Moscow, 1957.

S. B. Stopsky describes a simple method which allows determining incipient cavitation, its growth and sigma break equally well on a model as on a prototype. It consists of recording the amplitudes of pressure fluctuations in a narrow ultrasonic band of frequency. Describing his method Stopsky points out the great effectiveness of gaseous bubbles as pressure wave absorbers in liquids.

When the bucket discharge edges shed von Karman vortex streets, the pressure waves travel from these edges in all directions and are reflected from the water passage walls, coming back and superimposing on each other in a most irregular manner.

The water itself is a very bad damping medium; to absorb almost all of the input of the oscillatory energy coming from the impulses generated at the bucket discharge edges, the runner, casing, and the adjacent structures must develop a relatively high amplitude of vibration.

When gaseous bubbles are present anywhere in this zone of intensive pressure wave travel, they effectively absorb the energy of the waves. According to Stopsky, this can be explained first of all by the flow of heat from the bubbles to the surrounding water as well as by the dispersion and transfer of the sound wave energy to the bubbles. When a part of the energy input is absorbed by the bubbles, only the remaining part must be dissipated by vibration of the turbine and the adjacent structures. Therefore, the amplitude of vibration decreases and there is less noise.

According to this analysis, air admission and cavitation, both supplying bubbles, should be effective in reducing the vibration of the unit and the noise level. Furthermore, it can be theorized that it is not necessary to admit air exactly at the places where the trouble arises because vibration occurs not only due to the original waves created at the discharge edges of the buckets, but also in connection with the waves reflected from the steel walls. The wall reflecting a wave absorbs only a small part of the wave energy, the remaining energy travels back with the reflected wave which must bounce back and forth several more times before being completely dissipated.

In such a case it is immaterial where the vibration damper, consisting of a certain number of bubbles, is introduced as long as it is located in the space where the intensity of the wave travel is high.

If a given volume of air is going to be admitted, the best effect may be expected from its admission somewhere upstream of the runner. In this case it remains in the zone of intense pressure pulsation longer before it is washed away through the draft tube.

According to Stopsky, the size of the air bubbles undoubtedly is also of importance. Unfortunately, there is no known technique for controlling the size of bubbles. The natural frequency of the bubble oscillation depends on its diameter, and the bubble absorbs the maximum amount of pressure wave energy when its natural frequency coincides with the frequency of the pressure waves.

It appears that the several phenomena described by the author confirm the conclusions from the theory described in the foregoing, or can be explained by it. For instance, the sharpening of the entrance edges of the Denison runner buckets undoubtedly resulted in some local cavitation at certain heads and gate openings. Therefore, the vapor bubbles were present and, as the author observes, this sharpening of the entrance edge was very effective in reducing the noise and the turbine case vibration. The writer knows also that when testing models in modern high head laboratories the turbine often produces some high pitched noise at a high cavitation coefficient, sigma. At lower sigmas, but well above the sigma break, this noise diappears. This seems to indicate that (in this case) the incipient cavitation, occurring well above the sigma break, is sufficient to prevent audible noise.

Author's Closure

The author wishes to thank Mr. Swiecicki for his discussion of the effect of compressed air injection in reducing the vibration and noise level in turbine runners. The possible phenomena caused by sharpening the entrance edges of the buckets and its relation to compressed air injection into the water passage in reducing bucket vibration are very interesting. With this in mind the sharpening of the entrance edges of the buckets does not appear as desirable as originally considered.

The reshaping of the bucket trailing edges to the half-bullet-nose or 45-deg angle, as described in this paper, is not a cure-all for turbine vibration; however, experience has indicated that the modification can be useful to the operating engineer in economically reducing objectionable vibration and noise caused by bucket vibration to a more satisfactory operating level.

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