HYDRAULICS BRANCH
OFFICIAL FILE COPY

PAP-439

BUREAU OF RECLAMATION
HYDRAULICS BRANCH

OFFICE FILE COPY

when borrowed return promptly

MT. ELBERT TRASHRACK VIBRATION STUDIES

BY

ROBERT TODD

BRENT MEFFORD

Thomas J. Isbester

PAP-439

Aug. 1982

MT. ELBERT TRASHRACK VIBRATION STUDIES

Robert V. Todd 1/, Brent W. Mefford 2/, and Thomas J. Isbester 3/

Abstract

A finite element analysis was performed on a prototype trashrack to determine if the analysis could be used in the design stage to predict frequencies and mode shapes of vibration. Both laboratory and field tests were performed on the trashrack to provide comparative data of the vibrations in air and in water. The effects of added mass were apparent for heave modes resulting in reductions in frequencies of about 20 percent in the field tests as compared to the laboratory tests in air. Plunge modes were not affected by added mass. Due to the random nature of flow velocity field on the trashrack, no lock-in vibrations were observed in the field tests. The presence of an intermittent draft tube surge with vortex breakdown was found to be the most severe condition the trashrack was subjected to. The periodic surge did not produce adverse conditions on the trashrack. A finite element analysis of a proposed trashrack design will give sufficiently accurate frequencies and mode shapes for evaluation purposes.

Introduction

The Bureau of Reclamation's experience to date with trashracks has been with low flow velocities, usually less than 0.6 m/s. Under these conditions, there is insufficient energy in the flowing fluid to cause damage to the trashrack. Because of their suitability to provide power system regulation, reserve, and peaking power, pumped-storage facilities are becoming popular. Due to economic considerations, trashracks in these installations are being designed for higher velocities than 0.6 m/s. Depending on the overall operational parameters of the facility, there is a possibility of failure due to vibration. The source of vibration may arise from pulsations from the pump-generator in the form of intermittent or periodic surging, and water velocities resulting in vortex shedding from the trashbars.

Depending on the structural arrangement of the trashrack, failure may arise from the individual bars being excited at their fundamental frequency or the trashrack as a whole may be forced to vibrate at one of its natural frequencies. A number of papers have been written covering case histories of trashrack vibration failures with explanations of the

---

1/ Mechanical Engineer, Division of Design, Bureau of Reclamation, Denver, Colorado.
2/ Hydraulic Engineer, Division of Research, Bureau of Reclamation, Denver, Colorado.
3/ Hydraulic Engineer, Division of Research, Bureau of Reclamation, Denver, Colorado.

exciting mechanisms and the structures' response (see Appendix - Bibliography).

The Bureau needed a new design approach to take into account possible vibration of a trashrack under operational conditions. This investigation was undertaken to establish that design approach.

Proposed Design Approach

Initially the trashrack would be sized by the conventional approach based on a static head loading based on trash accumulation. Then a vibration analysis would be performed which would consider forcing frequencies; individual bar fundamental transverse frequencies; and natural frequencies and mode shapes of the trashrack under its proposed field conditions.

The determination of the trashrack's response to operating conditions is the most complex part of the analysis. It is dependent upon a number of factors which are difficult to predict at the design stage. These factors are the trashrack's boundary conditions or fixity, the velocity profile at the trashrack location, and the damping of the trashrack.

A program was proposed to obtain the natural frequencies and mode shapes of a prototype trashrack in air using both analytical and laboratory testing methods, and then comparing the results. The trahsrack would then be field tested to determine its response to actual operating conditions. Comparison could be made between the laboratory and the field results to determine the impact of the various factors mentioned previously.

Description of Trashrack Chosen for Tests

A trashrack from Mt. Elbert Pumped-Storage Powerplant was selected for the tests because it was economically feasible to utilize an existing trashrack located a reasonable distance from the laboratory. The trashracks - two bays of three trashracks each, one on top of the other - are located at the draft tube bellmouth, 40.84 m from the centerline of the pump-generator (see fig. 1). The draft tube is split by a center pier along its length; during generation, when operating at best efficiency the flow distribution at the trashracks is unsymmetrical with the higher velocities occuring on the left side (looking downstream.) The draft tube centerline is positioned 10° to the horizontal. The trashracks are located vertically in their guides; consequently, flow during generation will impinge on the transverse bars at an angle of attack of 10°. The upper trashrack in the left bay was selected because it required minimal handling compared with the lower trashracks.

The trashrack had been designed by the conventional method with no consideration given to fluid-structure interaction. The trashrack is 6.78 m wide by 2.5 m high made of seven 32- by 254-mm transverse load-carrying bars and forty 16- by 51-mm vertical bars. Loading is transferred to the side members, 152- by 102- by 16-mm angles, which bear on the steel guides.

The vertical bars have an aspect ratio of 3.2 which results in the flow forming a separation zone witnout reattachment taking place. The transverse bar spacing of 406 mm makes the fundamental transverse frequency of the vertical bars between welds equal to 334 Hz; this value is far in excess of any probable forcing frequency.

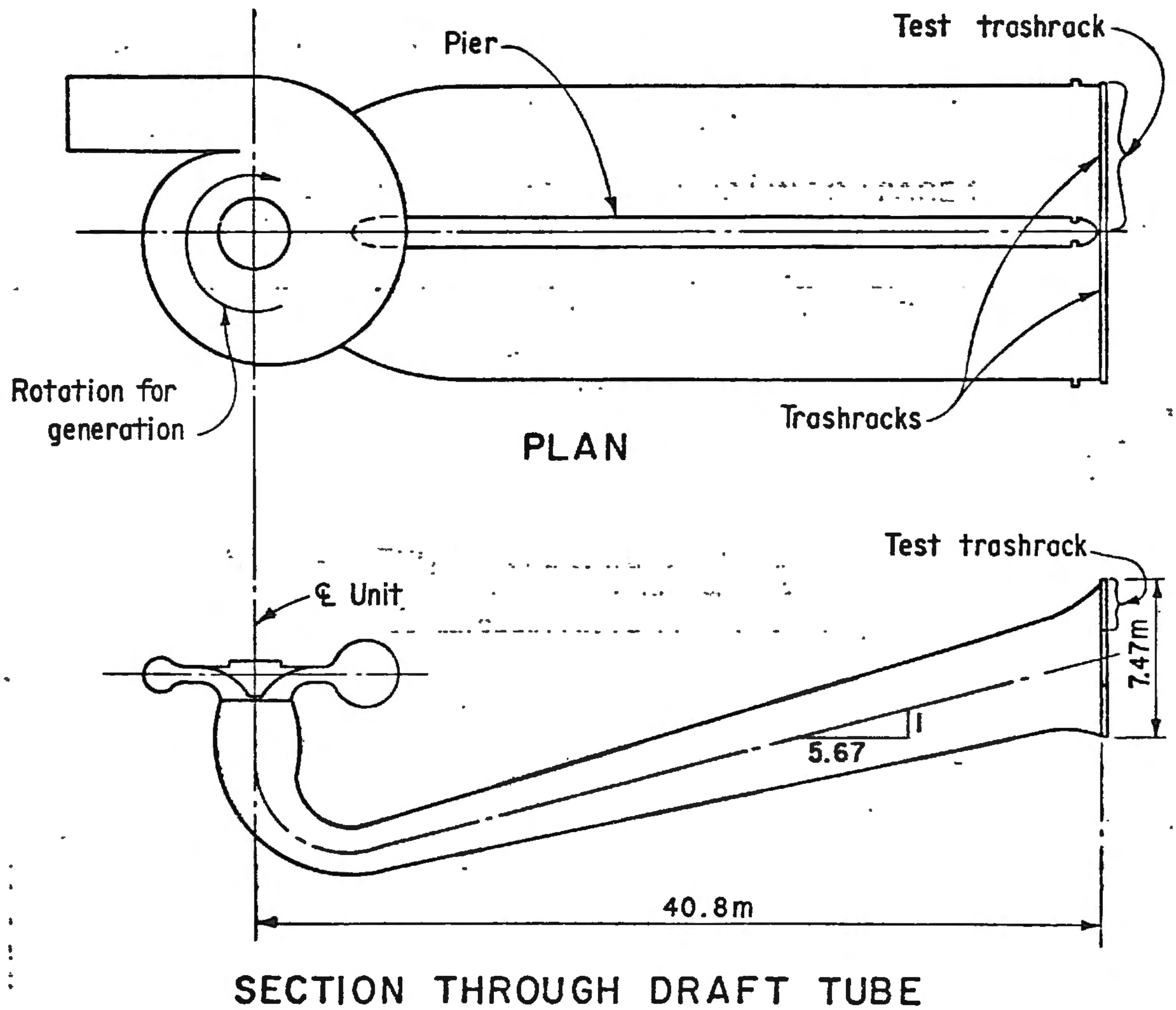


FIG. I – General Arrangement of Pump – Turbine and Trashracks

Choice of Boundary Conditions

The trashacks at Mt. Elbert are located in guides with no clamping devices securing them. The total transverse clearance between the trashrack and the guides is 32 mm laterally and 10 to 13 mm in the fore and aft directions. When the trashracks are subjected to flow, the drag will cause them to seat against the guides. Unevenness of the trashrack and the guides may result in a nonuniform bearing. The effect of possible uneveneness on the frequencies cannot be determined in advance.

Considering two sets of boundary conditions, it was planned to cover the actual response of the trashrack in its field location and have two different cases with which to compare the finite element model to the laboratory setup. The two cases were designated setup A, short sides of trashrack clamped; and setup B, the four corners clamped.

Finite Element Analysis

An in-house finite element program, STR5, was used to determine the natural frequencies, mode shapes, and moments of the trashrack for two sets of boundary conditions. STR5 is a structural analysis program for static and dynamic analysis of linearly elastic systems. The dynamic analysis part of STR5 provides a means of determining the natural frequencies and mode shapes for the structural system being modeled.

Initially a two-dimensional model was used. The complete trashrack was modeled using beam elements to represent the actual rectangular bars. The nodes were modeled at the intersection of the actual members. There were 294 nodes, each with 6 degrees of freedom resulting in 1764 equations to be solved. The computer can handle this size of problem, but it uses an excessive amount of time if more than three frequencies are required. The model was first run with the corners restrained in the x, y, and z directions to obtain the first three frequencies. The results indicated that there was no coupling between the heave and plunge modes. The terms heave and plunge are used to describe the motion of the vibrating trashrack. A heave mode takes place in the x, y plane, and plunge mode in the y, z plane. The axes relative to a trashrack are defined as: x parallel to the width; y parallel to the height, and z normal to the surface. Nodal lines are used to define the mode shape; for example, a (1-2) mode would have one vertical nodal line and two transverse nodal lines.

For the plunge modes, the rotation about the z axis and the displacements in the x and y directions were insignificant. For the heave mode, the rotations about the x and y axes and the displacement in the z direction were insignificant. By fixing three redundant degrees of freedom at each node, one type of mode would be obtained with half the number of equations to be solved. With the reduction in unknowns, a greater number of frequencies could be obtained from the same computer time. Running the program twice with the appropriate fixities, the first 10 frequencies for the plunge and heave modes could be obtained for one set of boundary conditions at an economical computer usage rate.

Two different sets of boundary conditions were required. The first, "test setup A," had the z displacements fixed along the short sides of the model. This simulated one of the laboratory setups where the short sides were clamped. It also approximated the actual installation conditions of the trashrack at the end of the draft tube. The second set of boundary conditions, "test setup B," had the x, y, and z displacements at the four corners fixed and simulated the second setup in the laboratory.

While running the laboratory tests, there appeared to be coupling between the heave and plunge modes. This was due, however, to the offset structural configuration. The vertical, 51- by 16-mm trashbars are welded to the short face of the 254- by 32-mm transverse beams. When the vertical bars deflect in a plunge mode configuration, the transverse bars are forced to rotate. These transverse bars have negligible torsional stiffness because of their rectangular shape, and due to the rotation, a vertical component of displacement is obtained which could be interpreted as a heave mode. This effect was simulated by utilizing a three-dimensional model.

Because of the node limitation in the STR5 program, only one-fourth of the trashrack was modeled. All of the mode shapes could be obtained by modifying the boundary conditions. Apart from the boundary nodes, the remaining nodes were allowed 6 degrees of freedom resulting in a model with 168 nodes having an average of 970 equations to be solved. Eight different sets of boundary conditions were required to obtain the plunge and heave modes for the two laboratory setups.

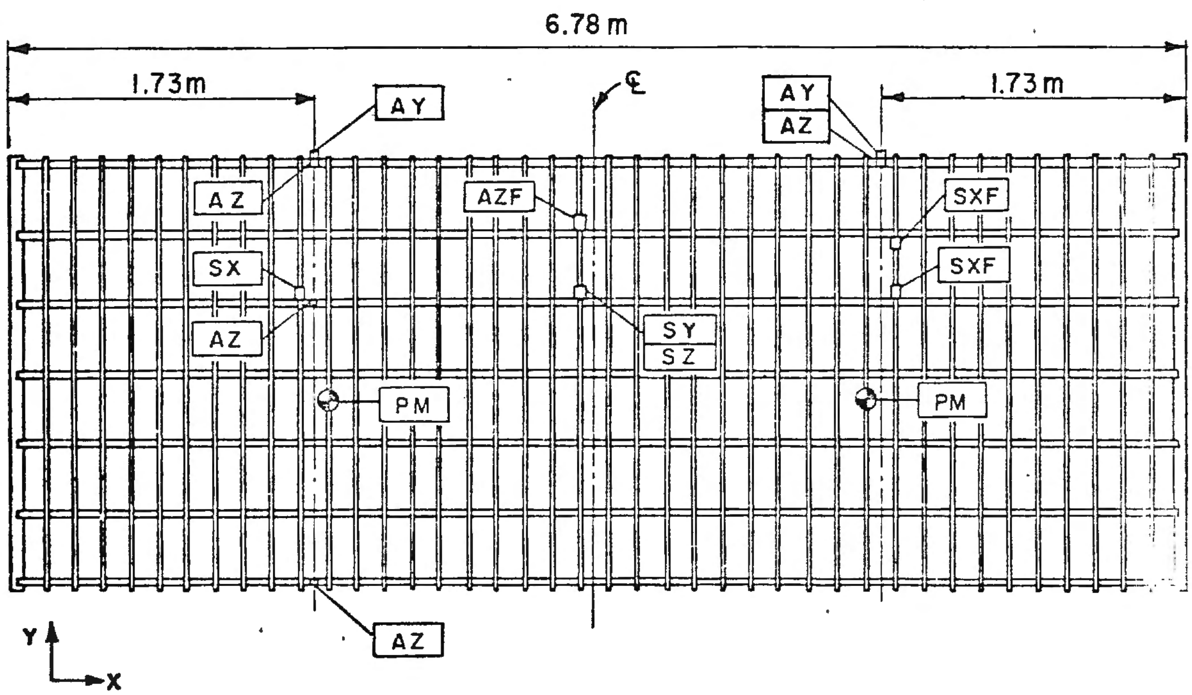
Laboratory Tests

The laboratory testing of the trashrack unit was accomplished in the vibration test building operated by the Concrete and Structural Branch of the Bureau of Reclamation Engineering and Research Center in Denver, Colorado. The trashrack was placed horizontally and supported on its short sides on 457- by 298-mm-wide flange beams to allow for access to the underside with electromagnetic shakers.

Six accelerometers and six strain gages were attached to the trashrack as shown in figure 2. In addition, a roving accelerometer was used to help define the mode shapes.

Two electromagnetic shakers were available to excite the trashrack. Some modes required two shakers either in phase or 180° out of phase.

In addition to data from the STR5 program, the transfer function capability of a spectrum analyzer was used to locate excitation frequencies for the laboratory study. The transfer function measurement yielded a ratio of cross power spectrum to autopower spectrum, or roughly the ratio of output to input at the selected bandwidth interval. Pseudorandom noise fed to an electromagnetic shaker was used to excite all frequencies within the total bandwidth. The transfer function output was also used as an indicator of the torsion present at each



AY = Accelerometer mounted in the y axis direction.

AZ = Accelerometer mounted in the z axis direction.

SX = Pair of strain gages to measure strains arising from bending about the x axis.

SZ = Pair of strain gages to measure strains arising from bending about the z axis.

--F = Strain gages used for field test.

PM = Propeller meter.

FIG. 2 Trashrack Instrumentation

excited mode by comparing transfer functions of accelerometers located with their sensitive axis at 90° from the trashrack excitation direction. This allowed for comparison and adjustment of trashrack boundary conditions on a real-time basis.

The remainder of the tests utilized discrete finely tunable sinusoidal excitation to drive the electromagnetic shakers and vibrate the trashrack.

Plunge modes were tested for setups A and B. Heave modes were tested for setup B only. Some predicted modes were well defined and easy to attain, while others were difficult to achieve or did not conform to the predicted shape.

Individual strain gage and accelerometer data were obtained with a measurement and control processor and stored on floppy disk for later FFT (Fast Fourier Transform) analysis. In addition, data were analyzed on an FFT analyzer, channel by channel during the tests.

The trashrack damping factor was determined for both the plunge and heave modes. After the steady-state data were obtained for the test frequency, the circuit to the electromagnetic shaker was opened and rack vibration allowed to decay. A retentive oscilloscope equipped with a Polaroid camera was used to record the rate of decay of the vibration. The traces were then analyzed using the logarithmic decrement method to obtain the damping factor.

Comparison Between Two- and Three-dimensional Finite Element Model Values and Laboratory Test Results

The frequency values obtained from the finite element models and the laboratory tests were tabulated and compared (tables 1, 2, and 3). There was good agreement in the case of test setup A except for the (1-3) plunge. In the case of test setup B, good agreement was obtained except for the (0-3) plunge with the three-dimensional model. Three heave modes obtained in the laboratory tests which correlated well with the two-dimensional finite element model were not obtained with the three-dimensional model.

Field Tests

The trashrack was installed on a new pump-turbine unit, and testing was accomplished during the startup phase which included loads of 25, 50, 60, 70, 75, 80, 90, 100, and 115 percent.

The instruments, consisting of six accelerometers, six strain gages, and two propeller meters, were installed on the trashrack according to details on figure 2. All lead wires were fixed to the rack bars with plastic wire ties and fiberglass tape to eliminate slack and funneled to the top centerline of the trasnrack. From this point, the wires were placed within a single polyethelene plastic tube which extended to the top of the afterbay wall and then to the instrumentation shack.

A 1:1 coal-tar epoxy was used to coat the accelerometers, strain gages, and lead wires. This coating fixed the position of the lead wires to the trashrack bars and prevented their vibration.

Frequency analysis of field data was performed using a combination of real time output from the spectrum analyzer and computer-controlled analog-to-digital sweeps of all transducer channels.

The spectrum analyzer was used to obtain accurate amplitude response. Time domain records were windowed using a flattop passband function before the FFT. Amplitude spectrums were obtained using long-term power spectrum averaging of successive FFT's.

Continuity between trashrack transducers was established using multiple-channel computer data acquisition. Time domain data sweeps of all transducers were taken at a 454-Hz rate. To minimize aliasing, analog filters were placed on each channel. Filter cutoff points were set to 110 Hz, dropping 32 dB per octave. The FFT's run on the time domain data yielded near simultaneous amplitude and phase data for all transducers.

Table 1. - Plunge mode frequencies of the trashrack for test setup A

Mode shape (1)	Two-dimensional finite element model, natural frequency in Hz (2)	Three-dimensional finite element model, natural frequency in Hz (3)	Laboratory results, natural frequency in Hz (4)
0-0	11.47	11.61	11.60
0-1	12.57	12.70	13.10
0-2	21.51	20.22	21.42
1-0	45.57	46.34	44.20
0-3	46.48	41.06	42.43
1-1	47.46	47.39	46.09
1-2	52.48	51.16	53.40
1-3	68.43	61.00	61.82

Table 2. - Plunge mode frequencies of the trashrack for test setup B

Mode shape (1)	Two-dimensional finite element model, natural frequency in Hz (2)	Three-dimensional finite element model, natural frequency in Hz (3)	Laboratory results, natural frequency in Hz (4)
0-0	10.42	10.50	11.00
0-1	12.54	12.46	12.94
0-2	20.81	20.57	21.20
1-0	27.80	28.42	32.20
2-0	43.96	-	42.17
0-3	46.34	32.88	42.13
1-1	46.72	46.43	45.66
1-2	51.08	50.30	50.41
1-3	67.22	60.58	64.08

Table 3. - Heave mode frequencies of the trashrack for test setup B

Mode shape (1)	Two-dimensional finite element model, natural frequency in Hz (2)	Three-dimensional finite element model, natural frequency in Hz (3)	Laboratory results, natural frequency in Hz (4)
0-0	7.11	6.90	6.92
1-0	15.21	14.94	14.43
2-0	25.11	-	24.78
3-0	37.29	36.18	36.81
4-0	52.03	-	51.94
6-0	89.07	-	88.41

Table 4. - Comparison between the trashracks' natural frequencies under laboratory and field conditions

Mode shape (1)	Laboratory results, natural frequency in Hz (2)	Field results, natural frequency in Hz (3)	Percentage difference between field and laboratory frequencies. (4)
Heave, 0-0	6.92	5.60	-19.10
Heave, 1-0	14.43	11.50	-19.60
Heave, 2-0	24.78	19.60	-20.10
Plunge, 0-2	a/ 21.42	20.90	a/ -2.43
	b/ 20.81		b/ 0.43

a/ Test setup A.
b/ Test setup B.

The location of the installed trashrack made the measurement of instantaneous velocity impractical. Current meters which produce an electrical pulse based on propeller rotation were utilized. The two meters used were calibrated for a range of velocities of 0.18 to 5.49 m/s, producing one pulse for every 20 revolutions of the propeller. The meters were placed on the trashrack as shown on figure 2. The large number of revolutions per pulse prevents measurement of instantaneous velocities but was considered adequate for these field tests. The current meters are unable to determine when flow might be moving in a reverse direction.

The pulse data were recorded on a two-channel oscillograph. The records were then analyzed for average velocity by taking a long record and counting pulses, and converting to average velocity. In addition, the maximum and minimum values were obtained from single pulses which covered the shortest and greatest time periods, respectively.

The velocity data confirmed the unsteady nature of flow in the draft tube. The percent deviation between the extremes and the average was considerably less at or near the 100-percent load condition.

While operating the turbine at 80-percent load and 63-percent wicket gate opening, some rather large accelerometer and strain gage readings were encountered. At the time draft tube surging was suspected, however, records of draft tube pressures were not being obtained. After reviewing the data from the pump-turbine model test report, it was determined that an intermittent surge with associated vortex breakdown was probably occurring in the draft tube. During December 1981, additional data were taken of draft tube pressure in the suspected range of operation and the presence of the intermittent surge confirmed. Intermittent surges in the draft tube occur during the breakdown of a helical vapor core vortex. The formation of the vortex and subsequent breakdown are random occurrences and produce large pressure pulsations during the collapse of the vapor cavity. During this phenomenon, rapid changes in pressure and velocity occur within the draft tube and are felt by the trashrack at the downstream end.

Comparison Between Laboratory and Field Results

Table 4 lists the modes and frequencies obtained from the field test and the corresponding laboratory results. Only four frequencies were encountered in the field tests; they occurred over the range of power settings from 60- to 115-percent load. A maximum average velocity of 2.29 m/s occurred on the left side of the trashrack at 90-percent load with a corresponding velocity of 1.83 m/s on the right side. The flow velocity fluctuated appreciably during one run. From the results, there appeared to be no lock-in at any frequency in the forcing functions. Resonant conditions were not present, the forcing spectrum being provided by the turbulent nature of the velocity profile.

The highest g loadings occurred for the 80-percent load case, which further testing indicated an intermittent draft tube surge was present.

The heave mode frequencies from the field test were approximately 20 percent lower than those obtained in the laboratory. Field and laboratory frequencies for the plunge mode were comparable. The reduced frequency when the trashrack is submerged may be interpreted as being caused by an increase in the mass of the trashrack or an added virtual mass. The virtual mass is a function of the mode shape; the heave modes which displace more water than the plunge modes are subject to a greater reduction in their frequencies when submerged. In the case of the heave modes, to obtain the reduction in frequency from air to water, the ratio of added mass to the structural mass was approximately 58-percent.

The stresses recorded in the field were extremely low; the highest values obtained were for the (1-0) heave mode with 80-percent load. The highest bending stress measured resulted in a maximum bending stress in the vertical bar of 1865 kN/m^2, which is well below the fatigue endurance limit. Good correlation was obtained between the stresses from the finite element models and the field test results for the (1-0) heave mode.

It was not possible to determine the degree of fixity of the trashrack from the field results. The vertical heave mode frequencies from the finite element analysis were found to be practically independent of the side fixity. There were differences for the plunge modes, but the plunge mode obtained in the field was found to have practically the same frequency as the two fixities tested in the laboratory.

Conclusions

1. The finite element analysis gave mode shapes, frequencies, and stresses that were in good agreement with those obtained from laboratory testing of a full-sized trashrack.
2. A two-dimensional model was sufficiently accurate compared with a more complicated three-dimensional model.
3. A finite element analysis of proposed trashrack designs will give sufficiently accurate frequencies and mode shapes for evaluation purposes.
4. More field testing is recommended specifically to cover the following situations: uniform velocity profiles equal to and greater than 3 m/s, and whether the rectangular bar with a minimum aspect ratio of 4 is susceptible to forming periodic vortices with sufficient energy to cause fatigue damage to a trashrack structure.
5. The random nature of the flow velocity field near the trashrack prevented the lock-in of vibration on any of the trashrack's natural frequencies.

Reference - Bibliography

1. Behring, A. G. and C. H. Yeh, "Flow-Induced Trashrack Vibration," Pump Turbine Schemes, Planning, Design and Operation, the Joint ASME-CSME Applied Mechanics, Fluids Engineering and Bioengineering Conference, Niagara Falls, New York, June 1979, pp. 125-134.
2. Crandall, S. H., S. Vigander, and P. A. March, "Destructive Vibration of Trashracks due to Fluid-Structure Interaction," Journal of Engineering for Industry, Transactions of the ASME, November 1975.
3. Fortey, J. W. and R. F. Tirey, "Flow-Induced Transverse Vibrations of Trashrack Bars," Civil Engineering, ASCE, May 1972, pp. 44-45.
4. Jones, G. V., "Vibration Study of Wallace Dam Trashracks," presented at the August 8-11, 1971 Proceedings of the Specialty Conference on Conservation and Utilization of Water and Energy Resources held at San Francisco, California, pp. 349-356.
5. Louie, D. S. and A. E. Allen, "Trash Rack Studies - Seneca Pumped-Storage Plant," ASCE National Water Resources Engineering Meeting, Phoenix, Arizona, January 1971, pp. 1-26.
6. Sell, E. E., "Hydroelectric Power Plant Trashack Design," Journal of the Power Division, Proceedings of the ASCE, POI, January 1971, pp. 115-121.
7. Vigander, Svein, "Trashrack Vibration Studies," Raccoon Mountain Pumped-Storage Project, Laboratory Report No. 1, Tennessee Valley Authority, Division of Water Control Planning Engineering Laboratory, October 1974.