Mitigation of Vibration on Bulb Turbine in Small Hydro Electric Power Plants

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***Abstract* - Small Hydro Power (SHP) development is being increasingly undertaken all over the world, especially in the developing countries, because of their various merits, varied application, and flexibility of utilization. Handling of large hydropower-generating units and keeping the size of the turbine generator sets are economically beneficial, which require higher running speeds and results in greater pressure differences between the two sides of the vanes of a turbine runner. These forces also cause vibrations of the stator, which are transmitted through the frame to any adjoining structure and causes damage to the bearing, stator, and rotor winding as well as reduces the lifetime of the entire machine. Furthermore, cavitations due to discharge cause the major vibration effects in most of the hydroelectric power plants. With modified Concrete support in the stay column, a smooth operation of the turbine generator sets can be achieved.**

Keywords: Bulb turbine, generator, cavitation, vibration control, hydroelectric power plant.

I. INTRODUCTION

The vibrations are set up in the hydraulic turbines due to intense pressure fluctuations caused by the growth and collapse of bubbles during cavitation. The vibration of the structures of turbine assembly is studied with the elastic properties of the structure to match the hydrodynamic properties of the flow [8]. There can be resonance between the cavitation phenomenon and the natural frequency of the turbine structure and concrete foundation. Vibration test can be carried out to determine the frequency that is likely to cause resonance in the turbine-supporting structure and foundation. For the case of cavitation induced in hydrodynamic pulsation of the flow system [25], the primary forces involved are the pressure forces and inertia forces. The cavitation-induced vibration and hydrodynamic pulsations occur in the hydro turbine due to pressure variation induced by large cavities [3]. In cavitation-induced resonances, the liquid properties exert a major effect on the cavity shape. The hydrodynamic pulsation induced by the cavitation causes significant changes in the type of flow [21]. To avoid resonant vibrations, it is necessary to seek some means of eliminating the hydraulic excitation force, instead of altering the natural frequencies. When this is not possible, alteration of natural frequencies for the turbine assembly may be carried out by suitably adding stiffeners to the machine foundation, as shown in Fig 1.

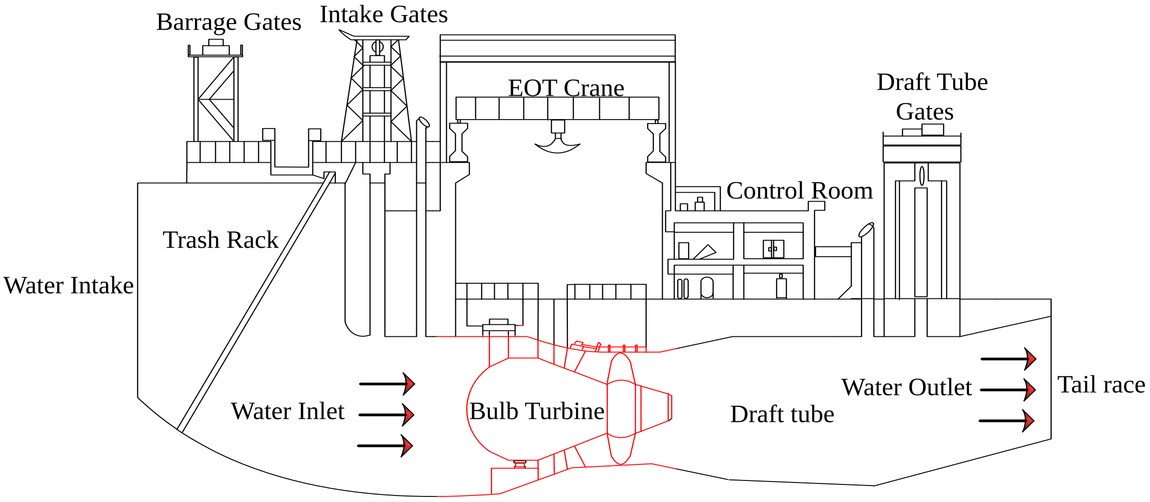

Fig 1. Layout of bulb turbine in a runoff river power house

In a hydropower plant, electrical or mechanical failures often lead to complete rejection of the generator load. Following such rejection, the turbine governor normally closes the turbine guide vanes to cut off the flow. This immediate action generates water hammer in the closed conduits, possibly resulting in excessive pressure rises that could burst the penstock and scroll casing. On the other hand, slow closure of the guide vanes subjects the units to a large increase in rotational speed as high as twice its rated speed. Traditionally and commonly, a surge tank is constructed to keep the transient pressure and rotational speed within design limits and ensure acceptable transient operation.

On large electrical generators, the critical speed has been found to be reduced by “unbalance magnetic pull” effects that occur when a rotor center line move off the center relative to the stator [26]; subsequently, the magnetic forces are unbalanced, similar to the effect of a negative stiffness spring. In addition, bearing pedestal flexibilities can also reduce critical speeds [23].

Fracturing in reinforced concrete will occur at a rather low level of tensile strain. Micro crack occurs in some local area in concrete at this stage. However, those cracks are still insignificant because the deformation of concrete is restrained by the reinforcement. Large cracks occur when the equivalent tensile strain exceeds the yield strain of reinforcement. The fracture indicator, determined by equivalent tensile strain, distinguishes the nonlinear deformation into three stages. It can provide a good indication of local failure of an RC component [16]. A block foundation has, in general, six degrees of freedom and, therefore, six natural frequencies (one corresponding to each mode of vibration). Three of them are translations along the three principal axes and the other three are rotations about the three axis. The vibratory modes may be “decoupled” or “intercoupled,” depending on the relative positions of the centre of gravity of the machine foundation and the centroid of its base area. The natural frequency is determined in a particular mode (decoupled or intercoupled) and compared with the operating frequency. In this study, the existing natural frequency of foundation is analyzed for the resonant condition [25]. Furthermore, a suitable modification to the foundation is carried out to alter its natural frequency to avoid resonance.

II. LOAD CALCULATIONS IN BULB TURBINE

A. *Thrust Load on Stay Column (P1)*

$$P1=F_r+0.5F_g-F_b \qquad (1)$$

Where, F_b: Force to bulb, F_r: Force to runner Load (ton), F_g: Gravitational force

A (No water inside the casing) : P1 = 0

B (Water filled-up unit in stand-still Condition) : P1 = 283

C (Unit in full-load operation) : P1 = 352

D (Unit in full load rejection) : P1 = 403

B. *Vertical Load on Stay Column (P2)*

In this calculation, shape and construction of the bulb is simplified. The weight of the bulb (W1), its location, the buoyancy of the bulb (F), and its location are as follows:

$$P2 = W1.\frac{L3}{L3} - F.\frac{L2}{L1} \qquad (2)$$

Where,

P2 = 160 T, W1 = 600 T, F = 350 T, L1: 3.8 m, L2: 1.9 m, and L3: 2.9 m

For condition A: $P2 = 500$ T, For condition B: $P2 = 283$ T,

For condition C: P2 = 300 T , For condition D: P2 = 300 T

C. *Horizontal Load by Short-circuit Torque (P3)*

The rotating torque by the generator acts on the bulb at the normal operation (full load) and short-circuit condition.

$$P3 = \frac{3}{2}.\frac{Tk}{L} \qquad (3)$$

Where

Tk: Generator torque

L : Distance of stay column load point = 13.6 m

For condition A: P3 =0 T, For condition B: P3 = 0 T,

For condition C: P3 = ± 30 T, For condition D: P3 = 30 T

D. *Moment by Short-circuit Torque (Mk)*

Moment of stay column by generator short-circuit torque is transmitted to concrete.

$$Mk = \frac{Tk}{4} = 350 \quad T \qquad (4)$$

III. ANALYSIS OF NATURAL FREQUENCY FOR THE FOUNDATION

A. *Analysis of Natural Frequency for the Foundation with Existing Stiffness*

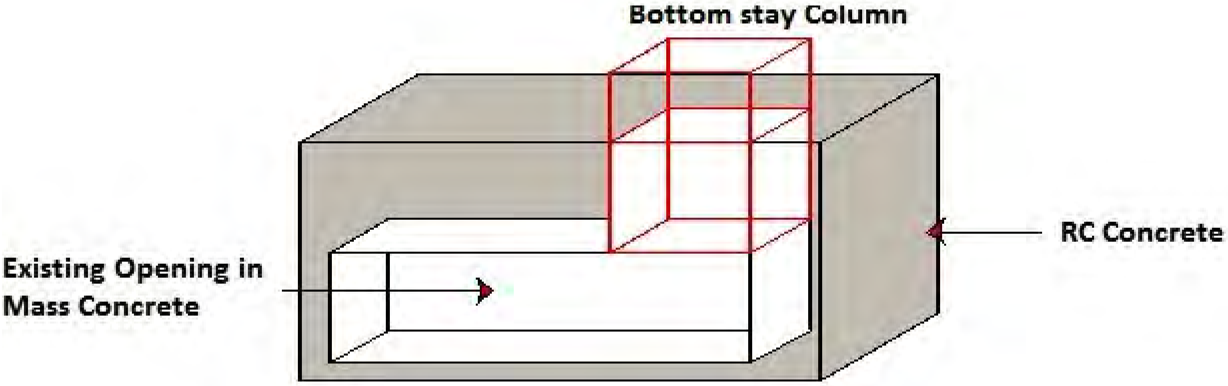

Fig 2. Existing foundation system

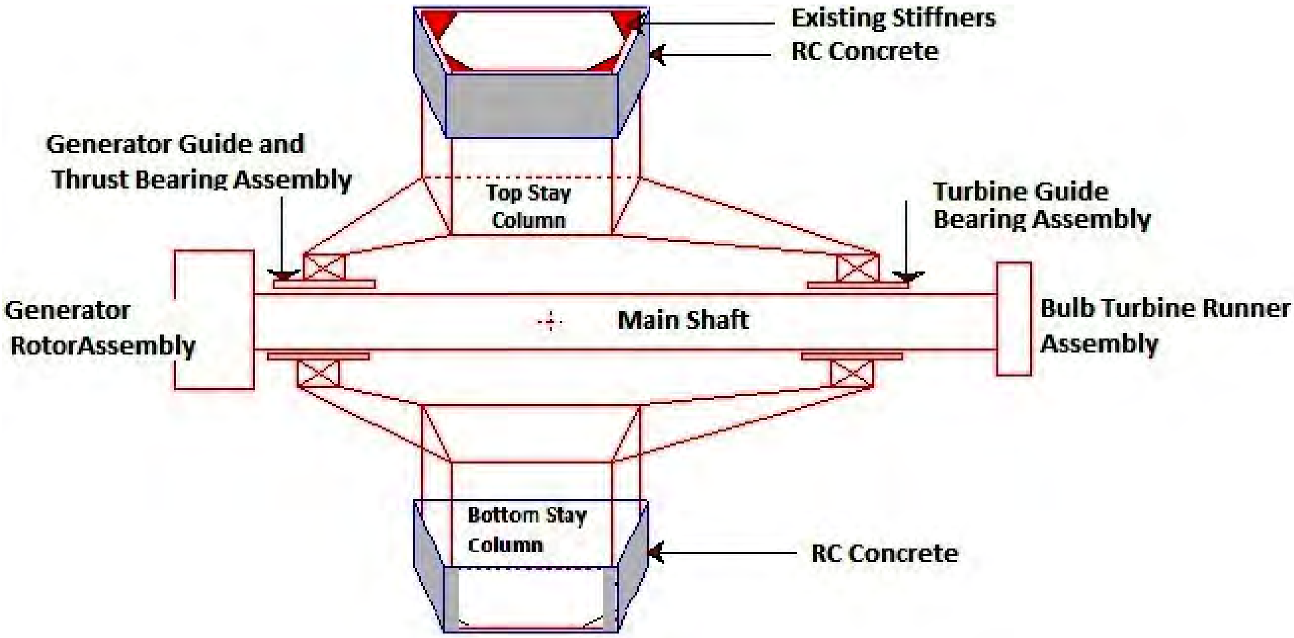

Fig 3. Existing stay column support layout

As per the IS.456.2000, "E_C" – Young's modulus concrete – is given as

$$E_C = 5000\sqrt{f_c t} \tag{5}$$

Where $f_c t$ = characteristics compressive strength of concrete.

For M_{20} concrete, fct = 20 N / mm^2

E_C for M_{20} concrete = $5000\sqrt{20}$

= 5000 × 4.472

= 22360.70 N / mm^2

E_C = 22.36 GP$_a$ = 22.36 × 10^5 T/m^2

E_C = 22.36 × 10^6 T/m^2

Stiffness of foundation $K_C = \frac{E_C A}{L}$ where A = area of foundation = 2.56 m^2.

For the condition shown in Fig 2, the foundation thickness = ((EL + 153.75) – (EL + 151.50)) = 2.25 m

L = 2.25 m, A = 2.46 m^2, E = 2.236 × 10^6 T/m^2

$$\text{Then, } K_C = \frac{E_C A}{L} = \frac{2.236 * 10^6 * 2.46}{2.25} T/m$$

$K = 2.445 \times 10^6$ T/m

The total weight of power house concrete = 1750 T

Then, static deflection $\delta_{st} = \frac{W}{K}$ $\quad \delta_{st} = 7.15 * 10^{-4} m$

$$f_n c = \frac{0.4985}{\sqrt{\delta_{st}}} = \frac{0.4985}{\sqrt{7.15 * 10^{-4}}} = 18.64 Hz$$

Natural frequency = 18.64 Hz

ω_n = 117.12 rad/sec

Critical speed of the machine N_c = 69.90 rpm

Hence, the analytical equation is given as

$$x(t) = (-)20.32 * 10^{-6} \cos \omega_n t + 72.87 * 10^{-6} \sin \omega_n t + \frac{F_0}{K} \qquad (6)$$

B. ***Analysis of Natural Frequency for the Foundation with Modified Stiffness***

For the condition shown in Fig 2 and Fig 3, the machine attains only 80 rpm during shutdown with

ω = 33.60 rad/s, with

$$x(t) = (-)20.32 * 10^{-6} \cos 33.60t + 72.87 * 10^{-6} \sin 33.60 + \frac{55}{44.867 * 10^4} \qquad (7)$$

$x(t) = 145.98\mu \approx 146\mu$

This 146 μ acts only for 2–3 s on the foundation, and hence does not harm the machine and concrete structure, when compared with coasting down peak vibration of 240 μ acting for 10–20 s at 70 rpm. As the natural frequency of the machine coincides with that of its foundation at the critical speed, a resonant condition at 70 rpm occurs. Now, the vibration at 70 rpm in the modified condition can be calculated by using the following equations:

$$x(t) = (-)20.32 * 10^{-6} \cos 33.60t + 72.87 * 10^{-6} \sin 33.60 + \frac{55}{44.867 * 10^4}$$

F_0 = 55 T at the transient condition during coasting down of the machines.

ω at 70 rpm = 29.40 rad/s. Therefore,

$$x(t) = (-)20.32 * 10^{-6} \cos 29.40t + 72.87 * 10^{-6} \sin 29.40 + \frac{55}{44.867 * 10^4}$$

The maximum vibration x(t) = 140.648 μ acts only for 2–3 s on the power house, which is safe, and the life of the civil structure is extended.

C. ***Analysis of Natural Frequency for the Foundation with Modified Concrete Mass***

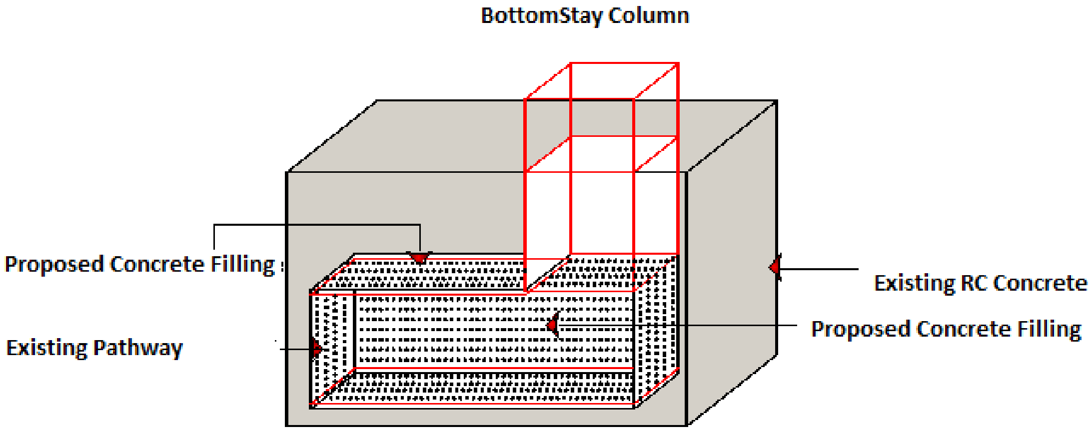

Fig 4.Modified foundation Layouts with Proposed Concrete filling

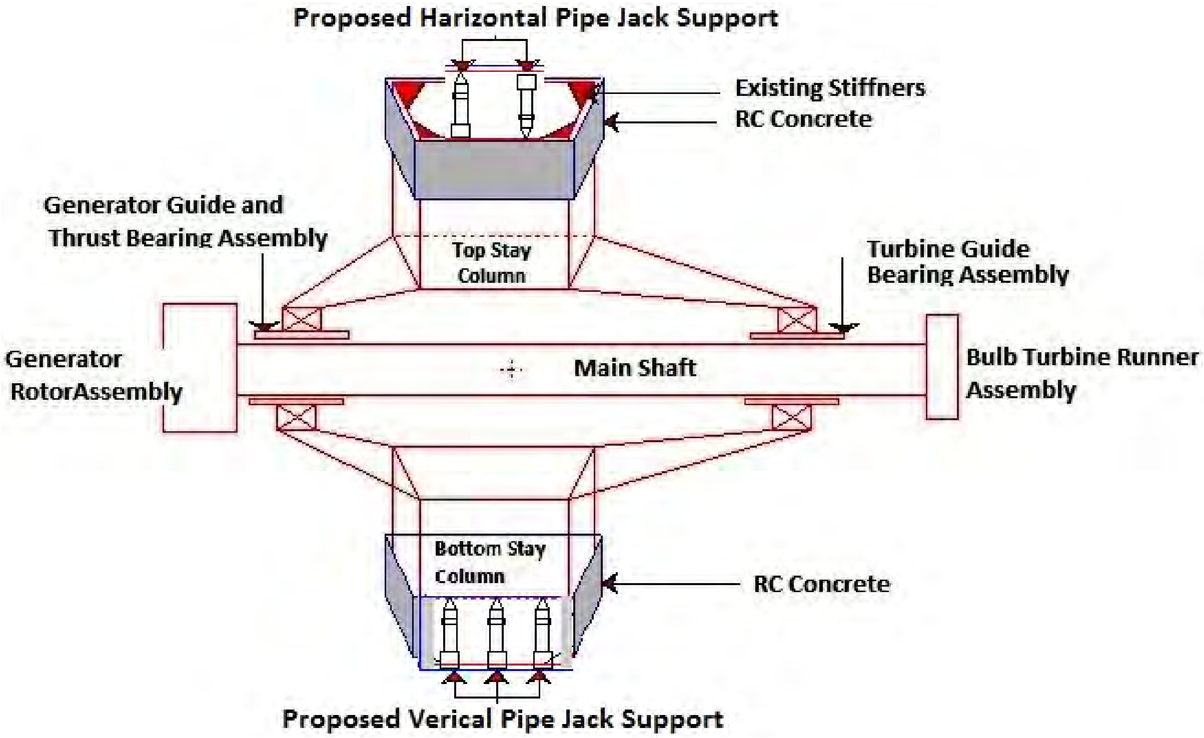

Fig 5. Proposed concrete filling foundation layout

By adding reinforced cement concrete of 9.54 m^3, as shown in Fig 4.and 5 to the pathway, the total weight of concrete foundation is increased by 25.758 T. The length of the concrete foundation (L) is increased by 1.440 m and the area (A) is increased by 0.54 m^2 as a result of the addition of this concrete mass. Therefore, the stiffness k is modified as follows:

$$K = \frac{EA}{L} = \frac{2.236 * 10^6 * 3.00}{3.69}$$

$$K = 1.80 * 10^6 \, T/m$$

$$\therefore f_n = \frac{0.4985}{\sqrt{\delta_{static}}} = 15.87 Hz$$

$$\therefore \omega_n = 99.72 rad / \sec$$

$$N_C = 59.50 rpm$$

Thus, the natural frequency of the foundation is reduced to 15.87 Hz. The equivalent critical speed on the machine is also reduced to 59.50 rpm and the resonance condition is avoided at 70 rpm. Now, the operation of the bulb turbine is safer and the life of the machine and its foundation are extended further.

IV. COMBINED VIBRATION MEASUREMENTS ON MACHINE AND FOUNDATION

G/V operating time during starting = 20 s,
R/V operating time during starting = 20 s
Duration of vibration = 20 s,
Critical speed of the machine = 70 rpm
Natural frequency for the machine = 18.67 Hz,
Guide vane passing frequency (f) = No. of G/V × critical speed in rpm;
i.e. dominant frequency : 16 × 70 = 1120 cpm,
Velocity of vibration (V) = f×D/ 19098.55 mm/s.

The vibration measurements made in the transverse, axial, and vertical directions with the existing stiffness and modified stiffness (by providing pipe jack supports) are shown in Tables 1–2. The relevant graphs are shown in Fig 6–15 for various types of vibrations at various power houses for different conditions.

Table 1: Vibration measurements in transverse direction

Speed	**Vibration measurements with existing stiffness - K (µ)**		**Vibration measurements with modified stiffness – K (µ)**	
	By actual measurements	**By analytical method**	**By actual measurements**	**By analytical method**
10	7.0	6.0	-	-
20	10.0	10.65	-	-
30	15.0	15.26	-	0.53
40	20.0	19.83	7.0	6.07
50	25.0	24.33	12.0	11.60
60	30.0	28.73	15.0	15.08
65	32.0	30.89	20.0	19.82
70	65.0	65.03	23.0	22.53
75	35.0	35.10	25.0	25.20
80	37.0	37.16	28.0	27.86
85	39.0	39.17	65.0	65.0
Coasting down vibration at 70rpm	240.0	239.16	140.0	140.648
Duration of Vibration in sec.	10 – 20	-	4 – 5	-
Operating condition	Dangerous	-	Safe	-

Table 2: Vibration measurements in axial direction

Speed	**Vibration measurements with existing stiffness - K (µ)**		**Vibration measurements with modified stiffness – K (µ)**	
	By actual measurements	**By analytical method**	**By actual measurements**	**By analytical method**
10	9.0	8.22	-	-
20	11.0	10.93	2.00	1.58
30	14.0	13.53	5.00	5.00
40	16.0	16.27	9.0	8.40
50	19.0	18.87	12.0	11.82
60	21.0	21.40	15.0	15.16
65	23.0	22.64	17.0	16.83
70	40.0	40.00	19.0	18.47
75	25.0	25.00	20.0	20.00
80	26.0	26.21	22.0	21.72
85	27.0	27.35	40.0	39.95
Coasting down vibration at 70rpm	214.0	214.13	137.0	136.6
Duration of Vibration in sec.	10 – 20	-	2 – 3	-
Operating condition	Dangerous	-	Safe	-

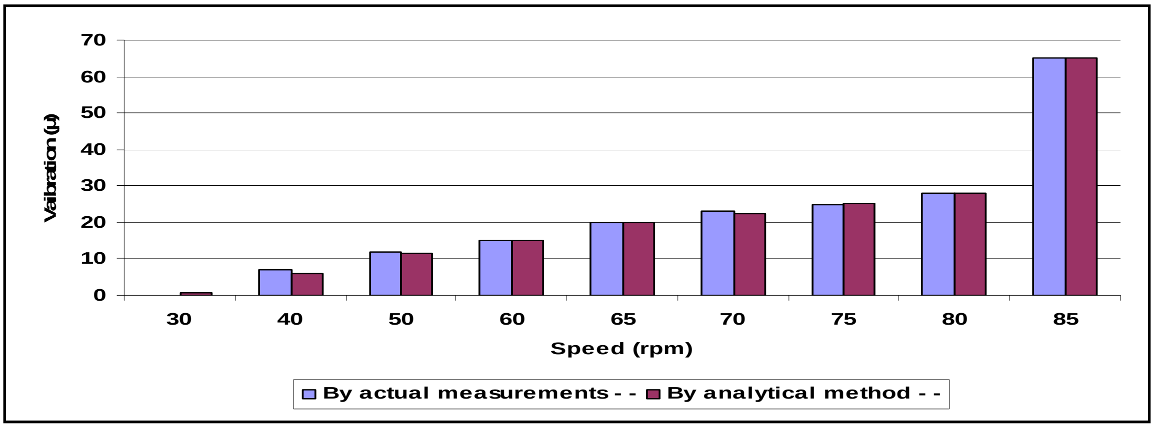

Fig 6.Vibration during mechanical spin in transverse direction with existing stiffness

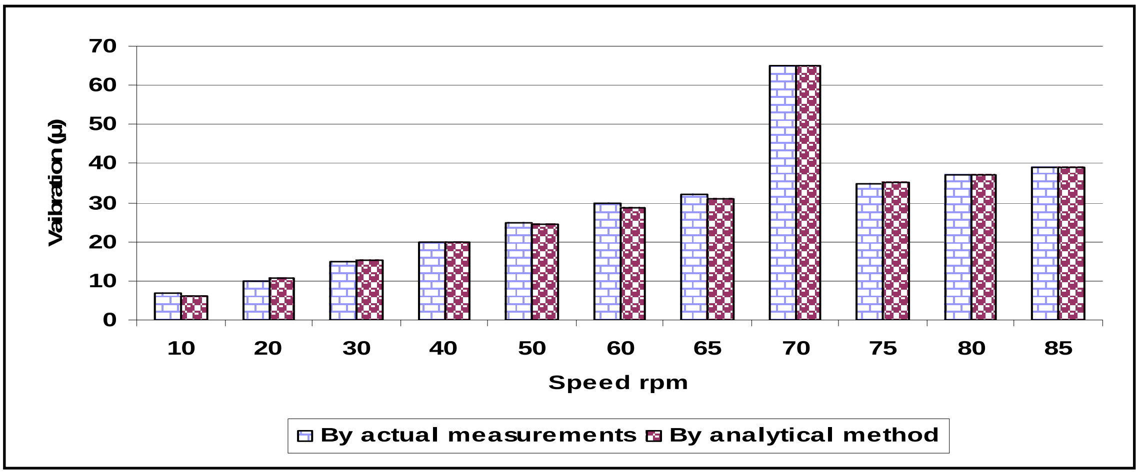

Fig 7.Vibration during mechanical spin in transverse direction with modified stiffness

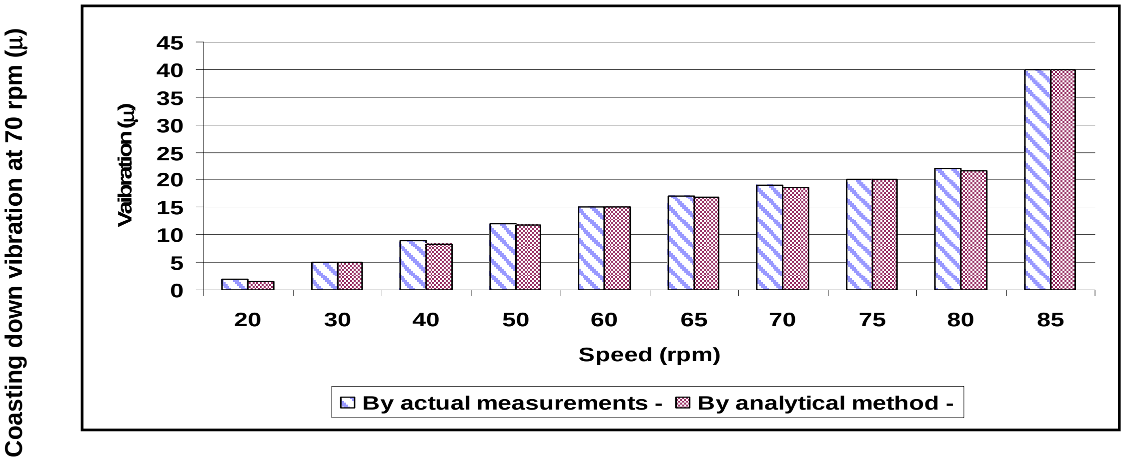

Fig 8. Vibration at shutdown in transverse direction with existing stiffness

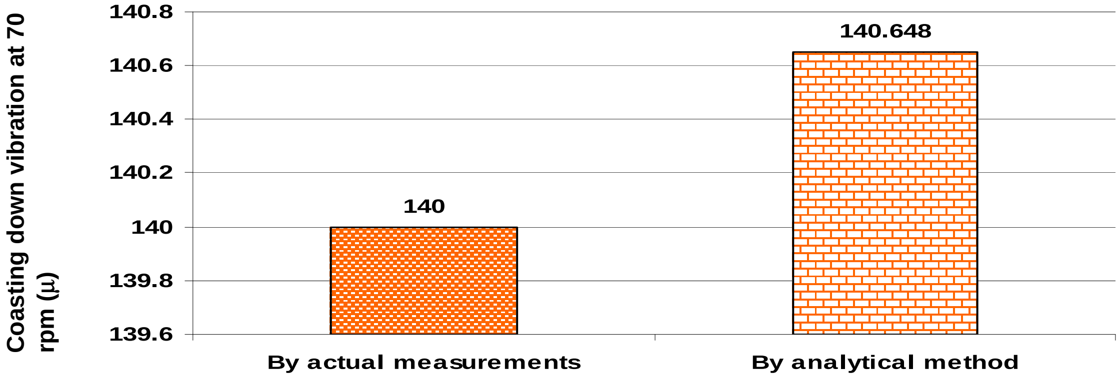

Fig 9. Vibration at shutdown in transverse direction with modified stiffness

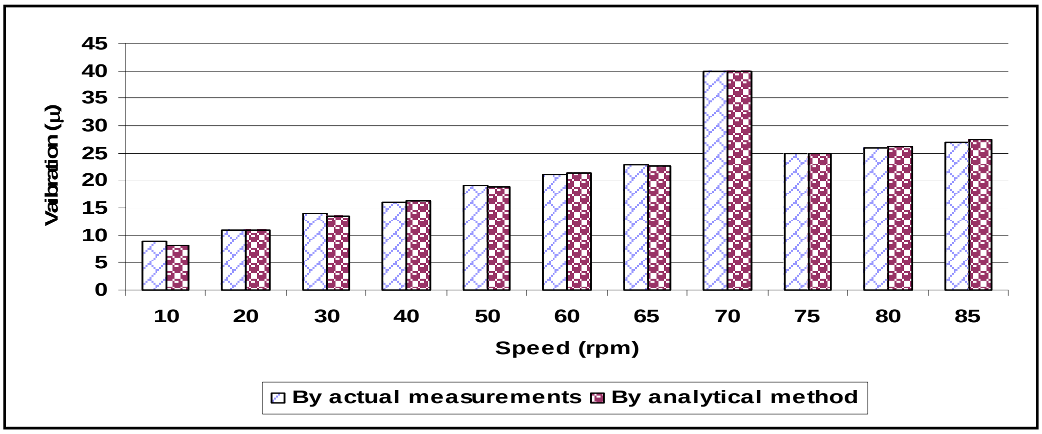

Fig 10. Vibration during mechanical spin in axial direction with existing stiffness

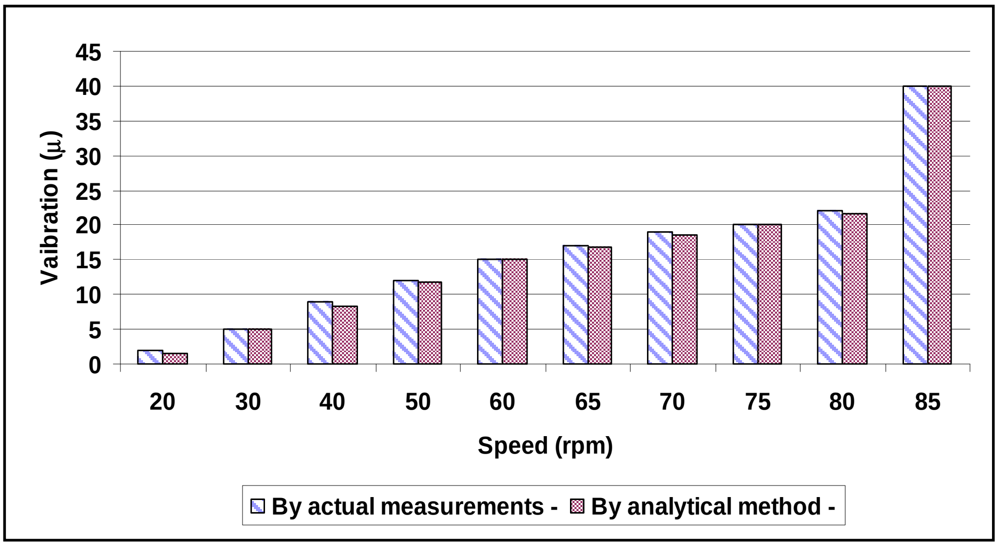

Fig 11. Vibration during mechanical spin in axial direction with modified stiffness

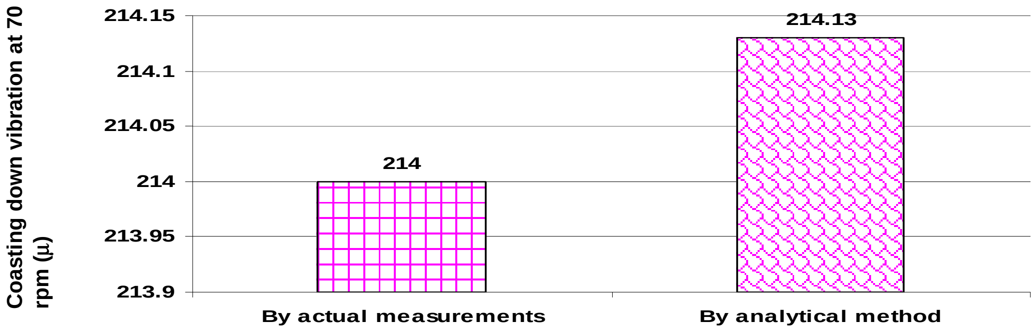

Fig 12. Vibration at shutdown in axial direction with existing stiffness

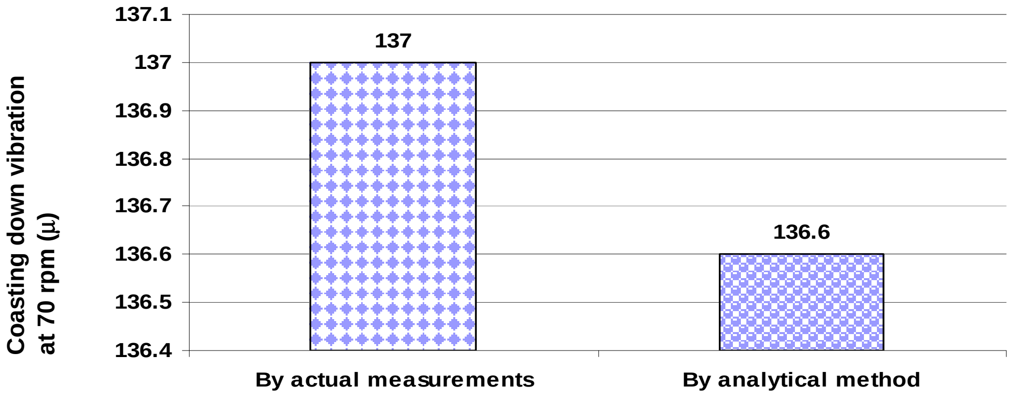

Fig 13.Vibration during mechanical spin in vertical direction with modified stiffness

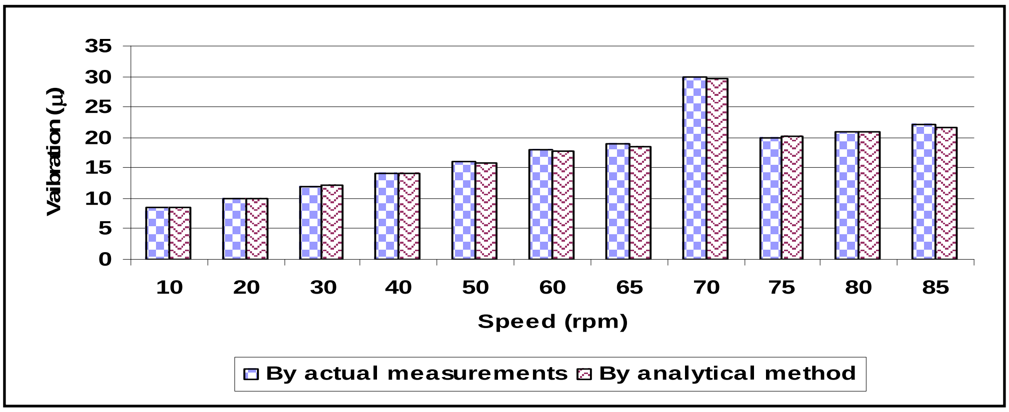

Fig 14. Vibration during mechanical spin in vertical direction with existing stiffness

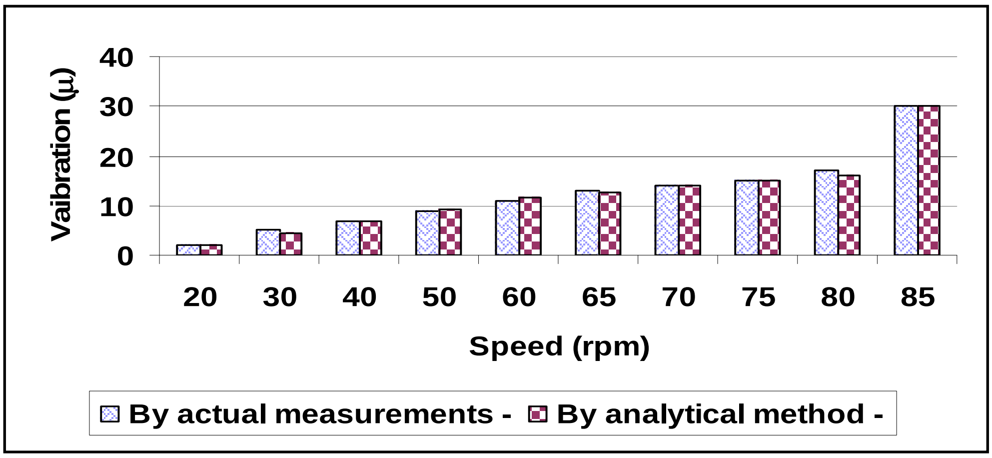

Fig 15.Vibration during mechanical spin in Vertical direction with modified stiffness

The vibration measurements made on the main shaft of bulb turbine and its foundation during starting and shutdown are shown in Table 3 and Fig 14 and 15.

Table 3: Vibrations measured in bulb turbine during starting and shut-down

Starting / Shutdown	**Displacement (D) µ**	**Velocity (V) (mm/sec)**	**Dominant Frequency (f) (cpm)**	**G/V passing frequency**	**Time duration of vibration (sec)**
Starting peak on shaft	65	3.80	1116.5	1120	20
Starting peak on foundation	2.05	0.12	1117.96	1120	20
Shutdown peak on shaft	240	14.0	111.34	1120	20
Shutdown peak on foundation	8	0.470	1122	1120	20

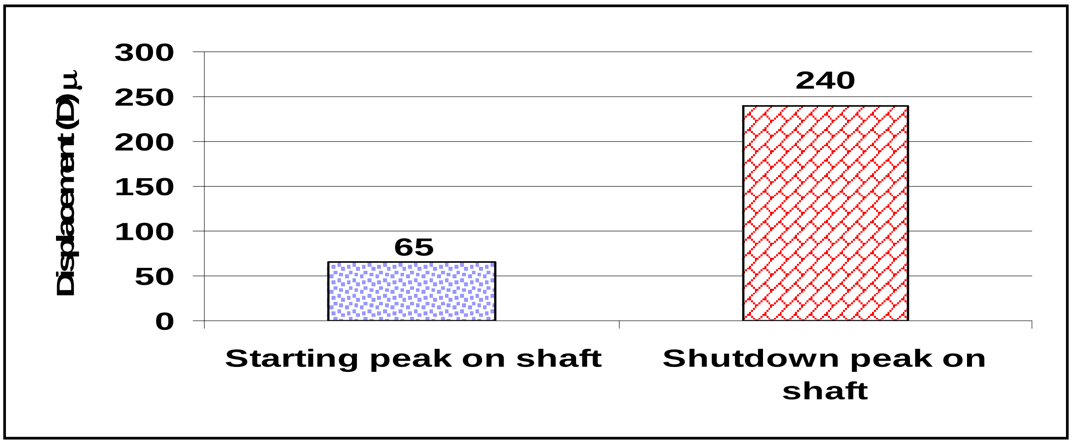

Figure 16. Vibration peaks on the main shaft of bulb turbine

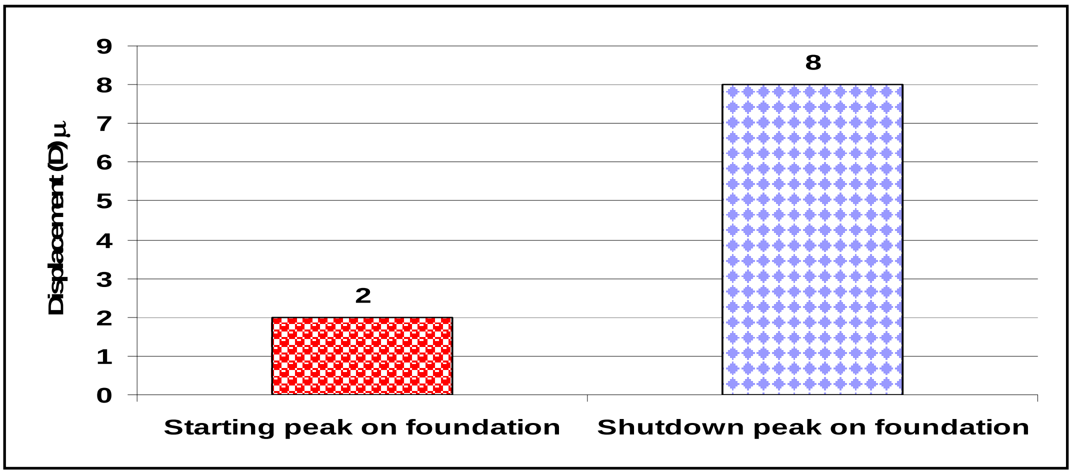

Figure 17. Vibration peaks on the foundation of bulb turbine

V. RESULTS AND DISCUSSION

When the turbine is rigidly bolted to the floor, the vibratory movement of the machine will be reduced, but the vibration transmitted to the floor will be large. This will produce harmful effects on the structure of the power house building. On the other hand, if a flexible support is provided for the turbine, the vibration transmitted to the floor will be considerably reduced, but this may cause significant motion to the machine itself during normal operation or during the starting and stopping stages. Therefore, some compromise has to be reached between the two requirements. This is achieved in design practice by selecting a suitable natural frequency for the machine foundation. For machines running at a steady speed, the degree of isolation is determined by a ratio (defined as the ratio of the operating frequency of the machine f_m to the natural frequency of foundation F_n). Thus, by choosing a suitable natural frequency, it is possible to obtain the required degree of isolation, which obviously depends on the environmental conditions at site.

The occurrence of resonance and the consequent effect on increase in vibration amplitudes is one of the most common sources of problem in turbine foundation. This is evidently due to faulty design based on improper estimation of design parameters such as stiffness of supporting media and unbalanced forces in the machine. The high groundwater table in barrage power houses is responsible for excessive propagation of vibration to the entire power house building and structure. Suitable structural measures are adopted to change the natural frequency of the foundation to ensure the required margin of safety from the operating frequency of the machine. The choice of structural measures depends on the site condition and the ratio of natural frequency to the operating frequency.

The peak vibration measured on the foundation during starting of the machine is 2 μ and occurs at 70 rpm in the existing condition. The guide vane passing frequency at 70 rpm (critical speed) is 1120 cpm. The velocity of the vibration during starting is calculated as 0.12 mm/s. The natural frequency of the foundation concrete is 18.67 Hz. The guide vane operating time during starting is 20 s and runner vane operating time from 100 to 0% is 20 s. The duration of vibration at the time of starting is 10–20 s.

The peak vibration measured on the foundation during shutdown of the machine is 8 μ and occurs at 70 rpm in the existing condition. The guide vane passing frequency at 70 rpm (critical speed) is 1120 cpm. The velocity of the vibration during shutdown is 0.47 mm/s. The natural frequency of the foundation is 18.67 Hz. The guide vane operating time during shutdown is 7–10 s and the runner vane operating time from 0 to 100% is 20 s. The duration of vibration at the time of shutdown is 10–20 s.

However, the peak vibration measured on the foundation during starting of the machine is only 0.5 at 75 rpm (rated speed of the machine) in the modified stiffness (K) condition. The runner vane passing frequency at 75 rpm is 300 cpm. Hence, the natural frequency of the foundation concrete is reduced from 18.67 to 15.87 Hz. The guide vane operating time during starting is 20 s and the runner vane operating time is 20 s. Thus, an increase in the stiffness of the foundation modifies the critical speed of the machine from 70 to 59.5 rpm and reduces the natural frequency of the foundation from 18.67 to 15.87 Hz. Hence, at this modified condition, machine operation is very safe during starting and shutdown because the critical speed of the machine has been increased to 85 rpm. Similarly, filling up the opening of the pathway with the reinforced concrete into the bottom stay column also produced identical results. Thus, the existing foundation has to be suitably modified to avoid resonance condition during the starting and shutdown to safely guard the machine and the entire civil structure of the power station.

VI. CONCLUSION

This study confirmed that increasing the mass of the foundation shifted the critical speed of the turbine from 70 to 59.5 rpm, and the natural frequency of the foundation was also reduced from 18.67 to 15.87 Hz. The maximum vibration measured at 70 rpm with the above-mentioned condition was only 140.648 μ, resulting in a higher difference of 100 μ, when compared with the existing condition. The duration of vibration was only 4–5 s, which did not impair the machine and its foundation. As the critical frequency of the machine increased to 85 rpm and that of the foundation reduced to 59.5 rpm, there was no chance of resonance condition during starting and shutting down of the machine. Hence, stiffness modification to the foundation or increase in the mass of the foundation concrete was the most beneficial method, as confirmed by this research study, which could be useful to safeguard the machine and its foundation for their life extension.

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