PROFIT MANAGEMENT AND CONTROL IN TRANSIENT AND STEADY
OPERATION OF HYDROELECTRIC PLANTS
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ABSTRACT

The method for hydro power and pumped storage plant profit on-line management and control were investigated. Vibrations of transient state (such as: starting, stopping, load rejection, over speed, runaway, etc.) are very important, and along with vibrations in steady state condition of hydraulic machines (pumps, turbines, reversible pump-turbines) must be considered. Available studies show that amplitudes of machine vibrations are increasing with time, changing the speed and acceleration of their amplification. This is caused by general erosion and corrosion or a disturbing rotor balance. When on-line measured vibrations are close to the limits, operation is only permitted under closed monitoring and supervision; if the limit is exceeded incident should be expected; the units should be maintained properly to prevent accident. This method and software are designed to increase profit, to protect a unit from accidents and incidents, and to instruct the plant and system technical and management staff what to do when selecting the most profitable operating points of the plant. Any problem could be recognized by the increased vibrations of the machine. The person in charge has only to react on them in time, and to take corrective measures.

1. INTRODUCTION

Amplitudes of mechanical vibrations are becoming larger with time increasing the speed and acceleration of their amplification. There are only few data how the vibrations of hydro unit’s bearings increase in steady operating conditions (Vladislavlev, 1979) and transient mode of operation (Ohashi, 1991; Rund, 1980). A model for profitability, and reliability analysis of hydropower stations is developed, correlating the displacement, speed, and acceleration of amplitude amplification to the measured frequencies and amplitudes of bearing displacement and acceleration. Any part of any machine could be monitored applying this method.

Modern personal computers are replacing the older versions of measuring devices. They can be used for monitoring, governing, controlling and protecting the power plant units, and they are affordable even for small plants. New software and hardware are developing very rapidly, and only those that can be easily updated and modified are lucrative.

There are a lot of books and papers on machine vibrations, and vibration’s measurements (Ohashi, 1991; Pejovic and Group of Authors, 1996; Vladislavlev, 1979) but only few publications are on transient vibrations (Gajic et al., 1996; Ohashi, 1991; Rund, 1980; Vladislavlev, 1979). A great number of books and papers have been written on mathematical models of transients, and vibrations, and their implementation (Ohashi, 1991 and great number of other books and papers) but only few of them guide to transient analyses (Pejovic et al, 1996; Pejovic, Boldy, 1992; Pejovic, Boldy, Obradovic, 1987, Pejovic, Gajic, 1998).

Limits for good vibration performance, for alarm release, and for trip are discussed in great number of standards, guides, books and papers. The experience has shown that the maximum continuous speed of shaft and bearing can be regarded as a decisive factor effecting the bearing loads; the maximum displacement must be evaluated as a function of continuous speed. The most frequent limits for trip are those for amplitudes of shaft and bearing displacements. When the measured vibrations are close to those limits, operation is only permitted under closed monitoring and supervision. If the limit is exceeded incident should be expected. In order to prevent them, the units should be properly maintained. During transients - start-up, shutdown, etc., different conditions usually exist and for a short time, the amplitudes are higher then the limits for continuous operation.

In the papers (Pejovic 1997, Pejovic, Gajic, 1998) steady operations of turbomachines were analyzed. These papers are introducing Equivalent Time of
Transients that shows how quickly a unit is growing old. High amplitudes of vibrations are dangerous. Corresponding Equivalent Times could be thousands time bigger than real elapsed time.

2. EXPOSURE RATE

Investigations on many plants have shown that the vibrations of hydro units increase with time of operation. This is caused by erosion and corrosion of the machines and their bearing, as well as by abrasive and cavitation destruction of the runner and parts of the turbine disturbing rotor balance. As the result, after a while, vibration of the unit reaches the boundary value for trip. The unit must be stopped and overhauling must be done (see Appendix: Limit values for vibration).

Recently, vibrations of transient state (such as: starting, stopping, load rejection, over speed, runaway, etc.) have become very important, and along with vibrations in steady state condition of hydraulic machines (pumps, turbines, reversible pump-turbines) must be considered. Fig. 1 (Rund, 1980; Ohashi, 1991) shows the allowable vibration amplitudes and exposure rate, \( E_R = 10^X \) for steady and transient operation.

\[
X = \begin{cases} 
\frac{s - 0.1}{0.4}; & s = \frac{v}{\omega} = \frac{a}{\omega^2} \text{ for } f \leq 3 \text{ Hz} \\
0.25 - \frac{v}{2\pi f}; & v = s\omega = \frac{a}{\omega} \text{ for } f > 3 \text{ Hz}
\end{cases}
\]

\( s \) - displacement, \( v \) - velocity, \( a \) - acceleration of bearing housing vibrations, \( f \) - frequency, and \( \omega = 2\pi f \) - angular velocity. Fig. 2 shows the corresponding charts of velocity and acceleration.

Lines of constant exposure rates fit a curve \( E_R = 10^X \). where

Amplitudes of about one-half of those given by the exposure rate of \( 10^0 = 1 \), are considered Excellent, while those on the curve are considered Normal. Strong vibrations are indicated by the curve for an exposure rate of \( 10^{-3} \), and Severe vibrations are those near to the curve for the exposure rate of \( 10^{-6} \).

The usual case of transient operation will produce vibration amplitudes in the strong range, and the components of the unit will be generally undamaged through unit life. Operation at higher amplitudes, or for longer total exposure, may lead to severe bearing damage, or to structural failure - serious damage to appurtenant members. The costs of these damages will increase with the length of exposure rates, and attached risk will be higher. In such cases, the possible remedial measures should be evaluated with the purpose to reduce the excessive vibration amplitudes. Until recently, there have been no published data on exposure rate related to normal mode of operation.

On the Fig. 3 (Vladislavlev, 1979; Ohashi, 1991), the allowable vibrations for steady continuous operation of hydro units with no exposure rate can be seen. This illustration is applicable to vertical and horizontal vibration of turbine, and generator bearings in two orthogonal directions: four zones are classified: A - Excellent, B - Good, C – Satisfactory, and D - Bad. In the zone Bad, exposure rate should be smaller than \( 10^{-5} \); this value is proposed since the existing statistical data for classification, as well as mathematical or graphical evaluations of exposure rate, which are currently available in the literature, are not directly applicable for this case.
The standards of turbine and generator vibration (see Fig. 4) show that the available values of double amplitudes are inversely proportional to the vibration frequency. The vibration standard is divided into four zones for turbine, and into five zones for generator: A - Excellent, B - Good, C - Satisfactory, D - Unsatisfactory end E - Impermissible.

In Fig. 5, recommended values for the maximum displacement of shaft vibrations are shown according to the VDI 2059 Guidelines, Part 4 (July 1981). Corresponding velocity and acceleration are increasing with shaft speed. At high speeds the limit could be too high. Figs. 2 and 5, as well as all other available Standards, Guidelines and new proposals do not have limits for acceleration.

Average lifetime between two inspections could approximately fit an exponential curve (Vladislavlev, 1979)

$$T_{av} = \frac{1}{C} \ln \frac{2 A_{VT}}{2 A_o}$$

(2)

where: $A_o$ - measured amplitude of vibration when unit was put in operation or after the overhauling, $A_{VT}$ - value for trip, $C$ - characteristic of increase of vibration. $C$ could be and should be measured for each particular unit. Statistical values, $C = 0.45 \times 10^{-4}$ $h^{-1}$ - for babbitt guide bearings, $C = 0.64 \times 10^{-4}$ $h^{-1}$ - for tree - plastic guide bearings, could be the first.
approximate values for input data. From this equation amplitude $A$ increase in time $T$

$$A = A_0 e^{CT}$$

(3)

Corresponding speed and acceleration of amplitude increase are:

$$\frac{dA}{dT} = CA = C A_0 e^{CT}$$

$$\frac{d^2 A}{dT^2} = C^2 A = C^2 A_0 e^{CT}$$

(4)

These equations are approximation only when amplitude $A$ and characteristic $C$ are functions of: $T$ - time, $F$ - frequency, $Q$ - flow, $H$ - pressure head, $n$ - speed of rotation, $n_s$ - specific speed, $f$ - natural frequencies, $\sigma$ - coefficient of cavitation, type of construction, quality of the unit, stresses, fatigue, etc.

The equation (2), (3) and (4) state that small values of $A_0$ and $C$ are desirable. Small initial amplitude of bearing vibration, $A_0$, and small characteristic of increase of vibration, $C$, means that high quality of the plant, machine and maintenance are obtained.

The measured on-line data, both in time and frequency domain, are treated in this up-to-date system, and analysis is quite easy. The most effective transformation of the measured data (in time domain) into frequency domain is done by using Fast Fourier Transformation (see Appendix: Fourier analysis of vibrations).

By considering: the equations (1 - 4), statistical data, and measured data for each particular unit, the method and the software have been developed and adopted for on-line and off-line monitoring (see Appendices: Computer program - steady operation, and Computer program - transient analyses).

3. EQUIVALENT TIME OF TRANSIENTS

The exposure rate indicates the ratio of on-line measured expired time to the equivalent time at rated vibration intensity. Vibrations of transient state (such as: starting, stopping, load rejection, over speed, runaway, etc.) become very important when limit for alarm is reached. If transient starts at $T_s$ and end at $T_e$ the equation

$$T_{Eq} = \int_{T_s}^{T_e} f(E_i, A_i, F_i, ...) dt = \int_{T_s}^{T_e} \frac{dt}{E} = \sum \frac{\Delta t}{E}$$

(5)

describes the equivalent time of transients.

Amplitude of measured acceleration at step by step transients (off line at nominal speed - synchronization - speed no load - 80 MW - 120 MW - 180 MW) and corresponding equivalent time is presented on Fig. 6. To the real measured elapsed time of 300 s = 5 min correspond the equivalent time of $\approx 6400 s \approx 107 \text{ min} \approx 01.47 \text{ h}$. In this five minutes transient the unit is one hour and 47 minutes older. Operating at normal conditions at rated output it could have produced 320 MWh.

4. STEADY OPERATION

Exposure rate, see Fig. 7, as correlation between the real time and reference time of operation, is the most important characteristic of a unit. It is a statistical data. Some standards, guidelines and technical papers consider vibration of upper/lower generator guide bearings, turbine guide bearing, and thrust bearing, and correlate them to the exposure rate, see Fig. 1 to 5, and other standards and guidelines.

The on-line measured data are compared to the previously measured data (several hundred hours earlier). Amplitudes of the measured vibrations are usually increasing in time, enlarging the difference between old and new data. They are highly
influenced by real time of operation, and corresponding exposure rate to the operating point. The differences, proportional to the times of operation and corresponding exposure rates for the particular bearing, generally increase in time when unit operates. Vibrations (amplitudes and corresponding frequencies), intensive cavitation, etc. have strong influence on numerical values of exposure rate

\[ E_R = E_R(T, A, F, Q, H, n, n_s, \sigma, \text{Type, Quality, Stress, Fatigue, } \ldots) \]  

(6)

The presented charts are based on equations (1 - 4), and the data from technical literature. They should be and could be improved for any plant, by analyzing files of measured and logged statistical data. The on-line measured and calculated data will be more reliable. Input data can be updating by adding new statistical analyses of measured machine characteristic; the method and the software will be improved (see Appendix: Accuracy).

5. PRODUCTION COSTS

Production costs, \( p \), are dependent on vibration intensity, and corresponding exposure rate, \( E_R \), which is increasing continuously in time. According to the literature and to our experience, the present chart is constructed, see Fig. 8. The application and the software should be updated by adding the existing statistical data on particular unit, which will give the more realistic picture.

Production costs, proportional to mean production cost \( c_M \) and exposure rate \( E_R \)

\[ E = \frac{c_M}{E_R} \]  

(7)

are dependent on vibration intensity, and they increase continuously in time.

Based on very low electricity rate \( r \) (4 Cents/kWh), fixed production costs \( c \) (1 Cent/kWh) and cost \( E \), proportional to the exposure rate, the profit \( p \) per kWh (USCents/kWh) is

\[ p = r - c - E(e, \sigma, \ldots) \]  

(8)

Even if the initial cost of a plant is high, the balance could be achieved by adequate electricity rate, low maintenance and replacement costs, reducing vibrations and exposure rates. At the same time, reduced vibrations and exposure rate reduce risk of damages and incidents.
6. PROFIT

The Chart, Fig. 7, shows that profit per hour, \( P_t = pP_t \), could be increased by on-line selected operating points within small amplitudes of vibration and high output, \( P \).

The turbine operating in the zone different from that of the best efficiency at operating point, \( \eta_{max} \), will result in water energy losses

\[
\Delta P_t = P_t \left( \frac{\eta_{max}}{\eta} - 1 \right)
\]

and profit losses.

The optimal turbine-operating zone is around 140 MW. Overload above 150 MW reduces profit and the unit could be gradually damaged by fatigue of material. Operating powers smaller than 100 MW will reduce profit, and will generate high water energy losses.

If the unit frequently operates close to 150 MW, or even over that limit, the system has not enough power, and new plants and additional units should be built and added to the system. If a unit frequently operates in zone between 0 to 100 MW, operation of unnecessary large number of units of the system will increase production costs.

Profit minimum in the middle at the output, \( \approx 90 \) MW corresponds to the draft tube surges.

7. CONCLUSION

The profit of a plant increases when production is high, but only until a certain limit. This limit is close to the rated point of unit operation; that is the case for the plants that are well designed. Overloading machine over the limit reduces profit or even turn it into losses. Partial lodes could produce losses too, see Figs. 7 and 8.

Bearing vibration amplitude, or that of any other machine part, increases in time amplifying its speed and acceleration. The computer program is designed to detect these problems, and it is based on the described method. Control software of hydro plant units is developed to instruct plant and system technical and management staff what to do when selecting the most profitable operating points of the plant, as well as to help them to increase profit.

By selecting the best exposure rate, the profitability and reliability of powerplants and related subsystems can be increased. By optimizing the system, one may increase availability, reliability, profitability, and production level.

The severity of unsteady operation of the units is described by the Equivalent Time of Transient.

8. ACKNOWLEDGMENTS

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9. REFERENCES


Fourier analysis of vibrations

![Displacement graph](image)

**Fig. 9. Displacement of guide bearing**

**Fourier Analysis of Displacement**

![Fourier analysis graph](image)

**Fig. 10. Fourier analysis**

Fourier analyses of measured bearing displacements, see Fig. 9 and 10, provides important data for machine behavior in steady and transient operation. Fast Fourier Transform - FFT is a remarkable efficient way of calculating the influence of frequencies and corresponding amplitudes on vibration severity, reliability and security of a unit and plant.

With the help of FFT charts, the experienced staff could have very important additional information on pump and power stations, and on unit itself. The software announces any trouble: the person in charge has only to react on it in time, and to take corrective measures.

**Computer programs - steady operation**

LABTECH CONTROL VISION Widow, see Fig. 10, gives information on profit and losses of the unit in operation. Any measured on-line data, site test data, and model tests could be put on the screen. The best operating point of the unit is determined by profit in function of power characteristic and on-line measured data. By following instructions, the profit could be increased obtaining the best results.

Any of applications and charts could be analyzed on-line, or saved in files for later investigation. The saved data could be very important in the case of incidents and accidents. Similarly to an airplane’s Black Box, they could help investigators to discover the order of events, as well as the cause of problems.

**Computer programs - transient analyses**

Transient conditions are classified into three hierarchies of increasing severity to the system...

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(Pejovic, and Group of Authors, 1996): Normal operating conditions, Abnormal conditions and Catastrophic cases. They can be easily saved and retrieved as well.

LABTECH CONTROL VISION Widow, see Fig. 12, gives on-line or off-line information on Equivalent Time for transients of the unit in operation. Any measured or calculated data could be put on the screen. Presented in the Figure is demo transient: Unit off line at nominal speed - Synchronization - power output 80 MW - 120 MW - 150 MW - 180 MW.

![Fig. 12. On-line or off-line Computer Screen](image)

Software and hardware could be continuously improved by applying new, updated methods and subroutines.

**Limit values for vibration**

Limit values are presented in the form of standards and guides, see Chapter 1: Introduction and Figs. 1, 2, 3, 4, and 5, as well as in standards listed in the References. For presented case vibration limits are: Excellent - 30 µm, Good - 70 µm, Satisfying - 120 µm, and Bad over 120 µm, see Fig. 7. When limit Good is reached, an alarm will be sounded, and the cause for the increased vibrations should be analyzed. If limit Satisfying is exceeded, damage must be expected and the unit is to be shut down for examination. In the range Satisfying, operation is only permitted under particularly close supervision.

**Accuracy**

The average accuracy is about 30% overall, obtained by using the initial method and software system and applying data from standards, guidelines, tests, technical literature and equations (1-9). By adding real measured and saved data, together with the information available from the staff experience, errors can be reduced very quickly to ≅ 5 to 10%.

Average accuracy, as well as individual accuracy of measured and calculated values, has no effect on profit since this method is a comparative one. Data acquisition and measurements are always performed with the same hardware and software. If the method and information are correctly followed, the maximum benefit will be achieved.