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Vibration Diagnostics of Electrical Rotating Machines

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Abstract- This article presents the vibration diagnostics of electrical rotating machines. The introduction describes the nature of the problem, state of the art in the field of vibration diagnostics, our contribution and achieved results. The theory of vibration is described in the second part. This part is divided into subsections called Harmonic oscillator, Forced vibrations, Free vibrations and Application. The third part deals with the measurement of vibration. In this part the answers to the most often asked questions related to the vibration measurement are listed. Facts introduced in this article are summarized in the conclusion.

I. Introduction

Facts introduced in this article are based upon author's long-term experience in the test department of the factory producing turbo-generators and mentioned references. This article is focused on the application of the theory of vibration in the engineering practice and the practical vibration measurement of electrical rotating machines.

The largest electrical machines work as turbo-generators in power plants or motors in heavy industry. The small motors work as drives in hand-operated tools or in household appliances. Their quiet operation is important for all of them regardless of their application. Vibration is one of the most important parameters indicating the machine condition. For instance, the increase of vibrations in the scale of micrometers is the reason for shut down of large machines. Customers also compare the products according to generated noise and vibrations.

Observations described in this article enable to perform the vibration tests step by step and choose the best procedures of measurement to get the correct results. These procedures result from the everyday personal experience with the measurement of electrical rotating machines.

Objective of this article is to summarize and present author's experience with the measurement of vibration at electrical rotating machines.

II. Vibrations of electrical rotating machines

The rotating part of electrical machines is called a rotor, the stationary part a stator. Vibrations are generated by a rotor unbalance or by the forces applied on a stator by the rotation of an electro-magnetic field. The rotor unbalance is the deflection of inertia axis from the rotors geometric centerline. The vibration is transmitted to bearings, a stator shell and other components of the machine. In the long term vibrations could damage the mechanical structure of the machine. Vibrations increase also a noise level in the machine surroundings. The measurement of vibration helps to monitor the machine's condition in the long term operation and also compare the vibration with the criteria in international standards.

Electrical rotating machines are AC, DC motors and generators. Rotors of electrical rotating machines are laid down in rolling or fluid film bearings. Rolling bearings are composed of round elements such as balls or rollers between two bearing rings. The fluid film bearings operation is based on the thin oil layer between the rotor journal and the bearing surface.

This article should give a short summary about the vibration theory and measurement according to my experience as a test engineer in factory producing large turbo generators (see Fig. 1).

Figure 1. Turbo generator during tests

III. Theory of vibration

Vibrations are a periodic oscillation around equilibrium position. Vibrations could be desirable such as vibrations of music instruments or undesirable such as vibrations of rotating machines.

A. Harmonic oscillator

Most simple oscillator is the system consisting of a rigid body hanged on a string (see Fig. 2). This system is able to perform movement only in linear direction (up and down), so it has only one degree of freedom.

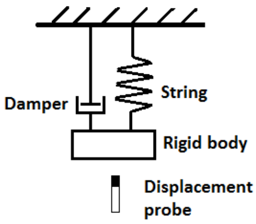

Figure 2. Harmonic oscillator

The time-displacement characteristic of this movement is a harmonic function (1). These characteristics are measured by displacement probes and are called waveforms (see Fig. 3).

$$x = x_0 \cos(\omega t) \qquad (1)$$

where:

ω	[1/s]	angular frequency of oscillation
x_0	[m]	amplitude of oscillation
t	[s]	time

The period T [s] is a time necessary for the system to perform one complete oscillation. Frequency is the count of oscillations per second (2).

$$f = \frac{1}{T} \qquad (2)$$

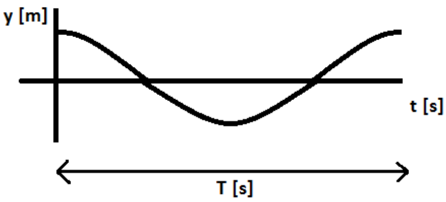

Figure 3. Harmonic waveform

B. Forced vibrations

Vibrations are derived into two types. For the forced vibration the time varying force is acting on the system. The frequency of the oscillating body is synchronous with the frequency of the acting force. For example rotation of a motor creates a forced vibration. The equation of motion defines the forces action on the oscillating body (3).

$$m\frac{d^2x}{d^2t} = F(t) - kx - b\frac{dx}{dt} \tag{3}$$

where:

m	[kg]	mass of a body
x	[m]	displacement of the body from equilibrium position
F(t)	[N]	time varying force
k	[N/m]	spring stiffness
b	[Ns/m]	damping coefficient

The left part of this equation is a Newton's second law of motion. It says that the force applied to a body is proportional to a mass of a body and its acceleration (4).

$$F = ma = m\frac{d^2x}{d^2t} \tag{4}$$

where:

a	[m/s^2]	acceleration of a body

On the right side of the equation of motion are a time varying force F(t) and expressions described in Hooke's law and Stoke's law.

Equation for the time varying force (5):

$$F(t) = F_0 cos\omega t \tag{5}$$

where:

F_0	[N]	amplitude of applied force
ω	[1/s]	angular frequency of applied force
t	[s]	time

Hooke's law states that a force needed to compress or extend a spring by some distance is proportional to a distance (6).

$$F = kx \tag{6}$$

Stoke's law states that the frictional (drag) force has the opposite direction to the force acting on the body and is proportional to the velocity (7).

$$F = bv = b\frac{dx}{dt} \tag{7}$$

where:

v	[m/s]	velocity

C. Free vibration

Free vibration occurs when the system gets just an initial impulse. The amplitude of this system would decrease to zero after some time according to the principle of energy conservation. The example of these vibrations is a guitar string. The body would oscillate at the natural frequency of the system ω_n. The natural frequency could be derived from the simplified equation of motion (without damping) where for *x* is substituted (8):

$$x = x_0 \cos(\omega t) \tag{8}$$

simplified equation of motion (9), (10):

$$ma = -kx \tag{9}$$

$$m\frac{d^2x}{d^2t} = -kx \tag{10}$$

after substitution (11):

$$m[-x_0\omega^2 \cos(\omega t)] = -k[x_0 \cos(\omega t)] \tag{11}$$

then (12):

$$\omega_n = \sqrt{\frac{k}{m}} \tag{12}$$

D. Application

The decrease of vibrations is one of the most often solved problems in engineering practice. The vibrations are decreased when the amplitude of oscillation is decreased. For the steady state of system in Fig. 1, the amplitude depends on these parameters (13):

$$x_0 = \frac{F(t)}{k}\frac{1}{1-\vartheta^2} \tag{13}$$

where:

ϑ [-] tuning coefficient (14)

$$\vartheta = \frac{\omega}{\omega_n} \tag{14}$$

The equation shows that the displacement of vibrations could be decreased in three ways. The first way is to decrease the force applied to the body. This is possible for example by rotating machines, where the applied forced depends on the rotor unbalance. In some cases, like a wind moving with a bridge, is this force out of control.

Another parameter is the system stiffness. The stiffer system has the lower amplitude of displacement. The stiffness could be increased for example by welding steel ribs on the machine.

The last parameter is the ratio of the force frequency and the natural frequency of the system. The force frequency is in most cases impossible to change, but the natural frequency of the system could be changed for example by adding a mass to the vibrating system.

IV. Measurement of vibration

Before any vibration test, some important questions are to be answered.

A. Which construction part of the machine is examined?

In most cases answer to this question also determines what type of vibration sensor will be used. The rotating parts of the machine (e.g. shaft of the rotor) could be measured only by relative (proximity) probe (see Fig. 4). This sensor is non-contacting. The examined part rotates under the probe and the relative position (displacement) between the probe attachment and the rotating surface is taken. The relative probes operate on the eddy current principle. The transducer transforms the probe output into voltage according to the sensitivity of the probe. This probe measures primary displacement, but the most vibrometers derives displacement to get velocity or acceleration.

Figure 4. Relative probe

The tests of stand-still parts (e.g. bearings or stator frame) give a bigger choice among vibrations probes. Test engineer could use the seismic probes - electro-dynamic or piezoelectric. If the examined quantity is the proximity between the probe and the component the relative probe must be used.

The electro-dynamic probe is attached directly on the tested construction part (see Fig. 5). The integrated coil is connected to the probe frame by couple of springs and is placed in the stand-still position relative to a seismic mass. The magnet in the coil's electromagnetic field copies the oscillation of the construction part. If the correct sensitivity is set, the coil velocity is proportional to the output voltage. The vibrometer could integrate the velocity waveform to get displacement or to derive to get the value of acceleration.

Figure 5. Electro-dynamic probe at a stator frame

The application of a piezoelectric (see Fig. 6) probe is similar to electro-dynamic probes. The main difference is that this type measures primary acceleration. The magnitude of electric charge of integrated piezoelectric crystal depends on traction, pressure and friction of this crystal. The spike inside the probe copies the oscillation of the construction part and generates electrical charge proportional to the acceleration of the probe. To convert the charge into voltage, the charge amplifier is needed. It must be known the sensitivity of the probe (acceleration to charge) and also the sensitivity of the amplifier (charge to voltage) to get the correct values. The integration of acceleration gives the values of velocity and displacement.

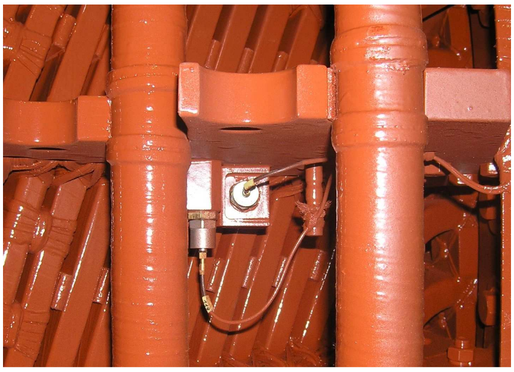

Figure 6. Piezoelectric probe at stator endwindings

B. In which quantity will be performed the measurement?

As mentioned, the vibrometers are able to display displacement, velocity or acceleration regardless to the chosen probe. If the specific quantity isn't determined in international standard, the selection should be performed according to the main frequency component. For instance, there is a given velocity magnitude $v = 1mm/s\ RMS$. The magnitude is constant for vibrations in the whole frequency spectrum (see Fig. 7). If this velocity is integrated, the result is the displacement (x in $\mu m\ RMS$), but frequency depending. The magnitude of displacement is higher at lower frequencies and lower at higher frequencies. The derived acceleration magnitude (a in $g\ RMS$) is also frequency depending. It is lower at lower frequencies and higher at higher frequencies.

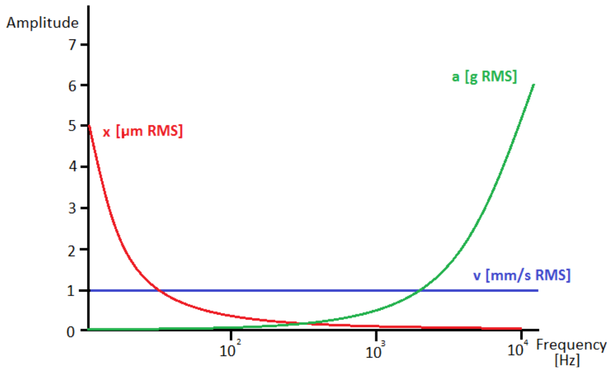

Figure 7. Frequency depending characteristics of displacement and acceleration amplitudes for determined amplitude of velocity

C. What is the purpose of vibration measurement?

One of the most important issues is to decrease the magnitude of vibrations. The rotor balancing is based upon the vibration measurement. The magnitudes of vibration are compared after each change of rotor mass. The intention is to eliminate the vibrations of the rotor.

Another purpose is to match the vibrations of the machine with the criteria of international standards or requirements of the customers. The observed positions are the rotor journals, bearing endframes and frame of the stator.

The last purpose is to monitor the machine vibrations in the long term period. The amplitudes of vibrations are recorded in prearranged maintenance intervals. Based upon trends of vibrations it is decided whether the service intervention is necessary or not.

V. Conclusions

Each vibration test has its specific requirements. The vibration of the rotor journal should be monitored by the relative probes as displacement. The rotating machine's bearing pedestals are usually measured by electro-dynamic probes as velocity. The vibrations of stator frame are usually measured as acceleration due to the significant content of higher frequencies.

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