ON OIL VISCOSITY INFLUENCE OF VIBRO-ACOUSTIC SIGNAL STRENGTH

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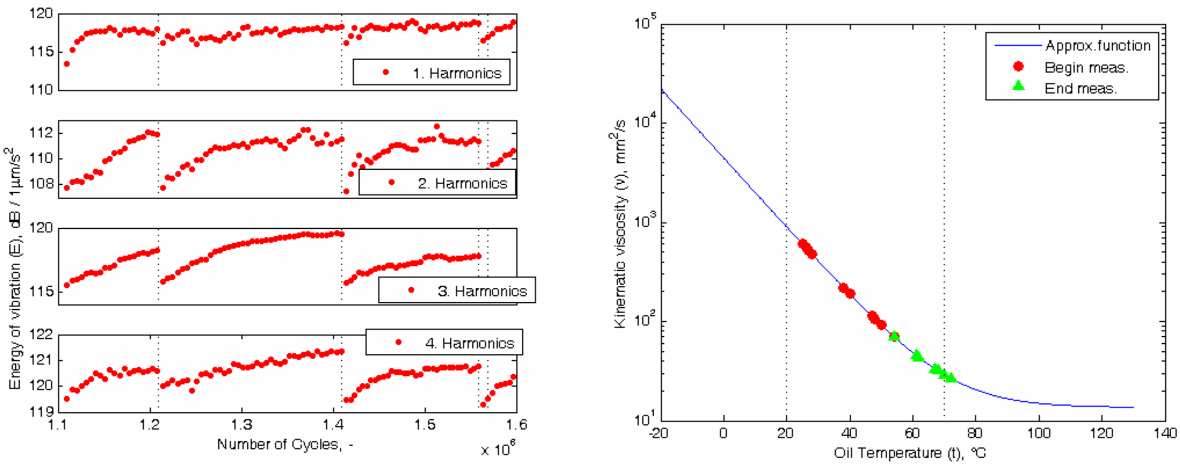
Abstract: The article analyzes the influence of temperature dependent oil viscosity on vibro-acoustic signal measured during tests on gearbox. The basic dynamic model was derived in order to analyze the problem from dynamic point of view. Comparing the measurements for different oil temperatures, the correction factor was introduced in order to compensate the attenuation of signal at measurements with low oil temperature.

1 Introduction

Gearboxes are one of fundamental elements of machines implemented inside small (kitchen) up to large scale (heavy industry) products. Therefore it is important to investigate the vibro-acoustical response of gearboxes and their impact on structures, humans and environment.

The test FZG gearbox (with closed torque flow) used in experiments is equipped with HCR (high contact ratio) gear wheels. This specific type of wheels have in meshing two pairs of teeth (transversal contact ratio is $\varepsilon_a = 2.003$) which reduces the force applied to each tooth in meshing. Consequently, it is supposed that the intensity of induced vibro-acoustic energy is smaller and noise of the gearbox (comparing with 'classical', i.e. $\varepsilon_a < 2$) reduced [1].

From the experiments performed, it was shown that the strength of vibro-acoustic signal is strongly dependent on operation conditions. Special care is taken to variation of oil temperature, as this is not directly controlled during measurements. It was shown in [2] and [3] that at low temperature, the attenuation of vibro-acoustic signal is significant due to high kinematic viscosity [Figure 1 (b)] and is reduced as the temperature increases. The conclusions were based on experimental results, where the signal was attenuated at machine start-ups. Figure 1 (a) presents measured data of energy at each harmonics for three sets of measurements (vertical lines show interruption of measurement).



(a) (b)

Figure 1. (a) Measured values of energy at each harmonics for three sets of measurement; (b) approximate V-T diagram of gearbox oil [3].

The continuation of the work is presented. The quantitative analysis based on simple dynamic model of meshing gears is summarized.

2 Dynamic model of meshing gears with oil damping included

There are varieties of dynamic models describing meshing gear wheels presented in the literature, e.g. [4], [5], [6], [7]. They vary from simple one or two degrees of freedom (DOF) systems up to complicated multi-DOF systems.

For the purposes of quantitative analysis of vibro-acoustic signal attenuation a simple 2DOF model, presented in Figure 2 (a), is used. In derivation, assumptions listed below were done:

- Teeth bending stiffness is negligible, just Hertzian (contact) stiffness, k_h, is assumed [4]:

$$k_h = \frac{\pi E b_w}{4\left(1-\nu^2\right)} \tag{1}$$

  with b_w width of the tooth, E Young's modulus and ν Poisson's ratio of gear wheel material;
- Oil film between teeth is modeled as a damping layer (linear function of oil viscosity [3]);
- HCR gearing have at meshing contact in two points and both lie on the same line of action [Figure 2 (b)];
- Contact forces (stiffness and damping) is acting on the line of action, which is tangent to the base circle in Figure 2 (b);
- Mass moment of inertia calculation is simplified as a solid disc with radius of pitch circle;

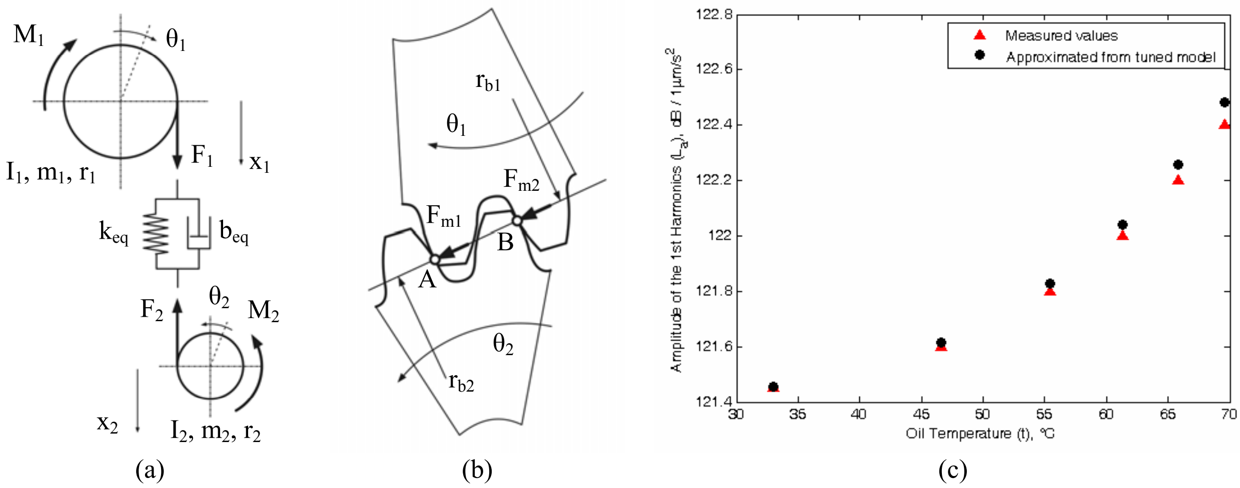


Figure 2. (a) 2DOF model of meshing gears; (b) action line and forces applied in meshing points (after [5]); (c) Amplitude of 1st tooth meshing harmonics as a function of oil temperature.

In the equation of motion for model presented in Figure 2 (a), first the contact forces F_1 and F_2 are defined using equivalent stiffness ($k_{eq} = k_1 + k_2$) and damping properties ($b_{eq} = b_1 + b_2$):

$$\begin{aligned} F_1 &= b_{eq}\left(\dot{x}_2 - \dot{x}_1\right) + k_{eq}\left(x_2 - x_1\right) \\ F_2 &= -b_{eq}\left(\dot{x}_2 - \dot{x}_1\right) - k_{eq}\left(x_2 - x_1\right) \\ x_1 &= \theta_1 r_1 \\ x_2 &= \theta_2 r_2 \end{aligned} \tag{2}$$

where coordinates x_1 and x_2 represent squeezing the oil film between the teeth and can be expressed in terms of angular coordinates θ_1 and θ_2.

Equation of motion defined in angular coordinates becomes:

$$
\begin{aligned}
I_1\ddot{\theta}_1 &= F_1 r_1 + M_1 = b_{eq} r_1\left(\dot{\theta}_2 r_2 - \dot{\theta}_1 r_1\right) + k_{eq} r_1\left(\theta_2 r_2 - \theta_1 r_1\right) + M_1 \\
I_2\ddot{\theta}_2 &= F_2 r_2 + M_2 = -b_{eq} r_2\left(\dot{\theta}_2 r_2 - \dot{\theta}_1 r_1\right) - k_{eq} r_2\left(\theta_2 r_2 - \theta_1 r_1\right) + M_2
\end{aligned}
\qquad (3)
$$

With excitation moments M_1 and M_2 satisfying condition of closed moment flow, i.e. $M_2 = r_2/r_1\, M_1$.

3 Tuning the model

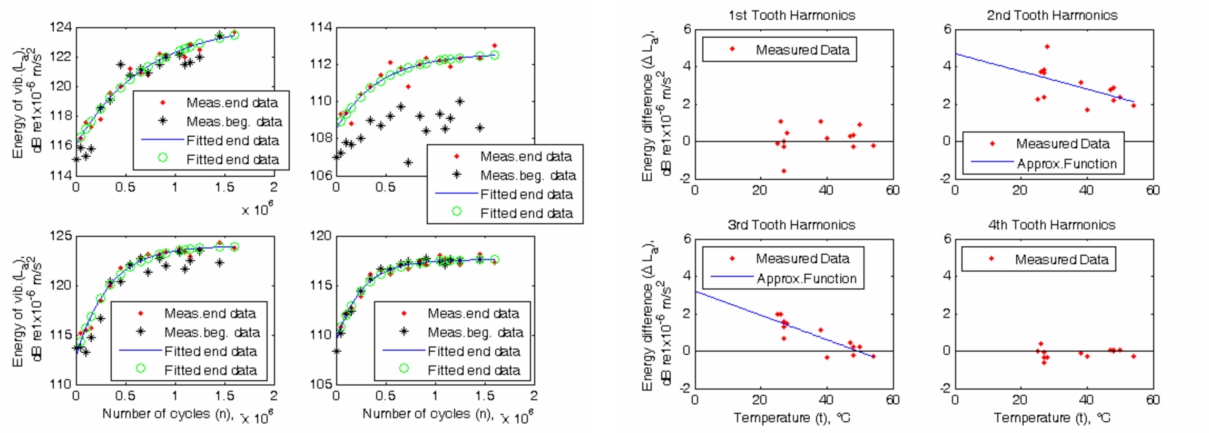
The model defined by Eq. (3) is semi-definite, i.e. it has just one natural frequency and mode shape. Therefore just first tooth harmonics is used for evaluation. The measured data are used in a procedure of model tuning.

First the natural frequency is tuned. The un-damped system is assumed. The initial value of stiffness is calculated using Eq. (1). The first tooth harmonics measured is f_{H1} = 261.5 Hz. The tuning coefficient c_t is used, in order to modify the system so, that the natural frequency from the model equals the tooth frequency measured. Using iterative procedure for natural frequency calculation, the coefficient value $c_t = 0.646$ was found. Then the corrected equivalent stiffness is $k_{eqC} = c_t\, k_{eq}$.

The second parameter to be tuned is the equivalent damping coefficient (b_{eq}). From experiments (Figure 1 (b), derived in [3]) the damping change for given oil temperature is known (it is linear function of viscosity). Then the estimate of damping coefficient can be based on the assumption of given amplitude change for given change in temperature [Figure 2 (c)]. As shown in Figure 3 (b), the second and third tooth harmonics is more sensitive to oil temperature change. Therefore the model should be extended to more degrees of freedom, in order to analyze also higher harmonics. To improve the accuracy of the model, more measured data with corresponding temperature change should be used.

4 Estimation of amplitude correction from measured data

The set-up used in experimental part of the project (FZG test rig) does not allow pre-setting the oil temperature. Therefore, to correct data recorded for low oil temperatures, the amplitude correction is searched.



(a) (b)

Figure 3. (a) Energy of vibration at the beginning and end of measurement as a function of temperature; (b) difference between the approximated energy and temperature.

First the estimate of correct energy values is done by fitting the measured data as shown in Figure 3 (a). Then the difference between the estimated correct value (from fitting function) and deviated value (measured at lower temperature) is plotted in Figure 3 (b). It can be noticed, that the first and fourth harmonics are correct (correction is around zero). However, the second and third harmonics need to be corrected using approximate function shown in Figure 3 (b). This correction needs to be used in evaluation of all data measured for low oil temperatures.

5 Conclusions

A simple two degree of freedom (DOF) semi-definite dynamic model of meshing gears was derived in order to analyze the influence of temperature on attenuation of vibro-acoustic signal intensity. Measured data were used in model tuning. However, just the approximate solution for the first tooth harmonics was analyzed. The improvement in estimation of stiffness and damping (as a function of temperature) as well as calculation of moment of inertia can improve the results. In future, improved model (extended number of DOF) may be used for prediction of vibro-acoustic properties of the gear box (temperature dependence, level of damage, etc.).

The temperature dependent correction parameter was derived from measurements, in order to correlate the data recorded at the temperature not high enough to eliminate signal attenuation. The correction will be used for analyzes of data measured on FZG test rig.

Acknowledgements

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