EXCITATION OF BLADE VIBRATION UNDER ROTATION BY SYNCHRONOUS ELECTROMAGNET

Luděk Pešek*, František Vaněk*, Vítězslav Bula*, Jan Cibulka*

This paper presents the procedure for designing electromagnetic bladed wheel excitation. This procedure comes from phase-synchronization of multiple electromagnets distributed around the wheel with a movement of the blade to obtain its resonant vibration. This procedure can be used with merit for dynamic tests of inter-blade couplings. The verification was performed on the tested wheel using two-point electromagnetic excitation of blades under rotation.

Keywords: *blade, vibration, excitation, electromagnet*

1. Introduction

The investigation of the dynamics of bladed wheels and the development of the vibrodiagnostic blade equipment is performed on physical models of the bladed disc in our laboratory. To evoke the wheel vibration main attention is focused on the excitation by magnetic field [1], [2]. The operational excitation of blades by passages of periodically distributed stream field is described in [3] and in laboratories it is often simulated by permanent magnets equidistantly distributed around a wheel circumference and placed in vicinity in front of the blades. For permanent magnet excitation of resonance vibration of the wheel with eigenfrequency ω_k and the rotational speed Ω the angular span β between magnets must hold [1]:

$$\beta = 2\pi \, \frac{\Omega}{\omega_\mathrm{k}} \; . \tag{1}$$

However, in connection with a usage of modern bladings with blade to blade connections in shroud by dry friction or by riveting [4], [5], [6], the demands appear for dynamic testing of the blades with a control revolution speed independent excitation. This excitation aims to dynamically test bladings for evaluation of the damping effect of the coupling on a given eigen-mode of vibration. It could lead to an optimal blade-to-blade coupling design for the vibration suppression. As the control excitation of the blade vibration under rotation the alternate magnetic field of electromagnet was chosen. The effective placement of such electromagnet must be in a safe distance from the blades to prevent damage of the rotating vibration blades. So, the sufficient gap, stiffness of blades, and non-continuous actuation of the attraction force during wheel revolutions require an electromagnet of higher power and a bigger size or bigger distribution of the excitation forces around the wheel circumference.

Based on these requirements and our experiences with the magnetic excitation of resonance vibrations of the bladed wheels the excitation system with electromagnets UTM4 was

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developed for the test wheel stand in Škoda Power Works. The system consists of electromagnetic exciters placed on the stator against the bladed wheel, strain-gauge displacement sensors in the vicinity of the blade root and slip-ring transmission of the sensor signals to the stator.

All electromagnet poles are situated radially, along the length of the blades. Then, their magnetic flux is enclosed over the blades so that electromagnets can act by attracting forces on blades mainly in axial and partially in circumferential directions. The forces have either frequency or double frequency of alternate supply current of coils. Measurable displacement of the forced blade vibration is achievable only in the resonance. The displacement measurement by the half-bridge with Si strain-gauges of P and N types was used for high sensitivity measurement.

2. Force actuation of electromagnets on rotating blades

The electromagnets act by force pulses on each blade at passages of the blade around them creating a periodic pulse train. The force does not increase by jump at the blade arrival and departure from the electromagnet (see Fig. 6), but in the first approximation we can consider these pulses as rectangular with the amplitude F_A and width τ with period T_0 (Fig. 1) which is the time of the passage between neighboring electromagnets (Fig. 2). The spectrum of the pulses is described by Fourier's series [7]

$$F(t) = \frac{F_\mathrm{A}\,\tau}{T_0} + \sum_{n=1}^{\infty} \frac{2\,F_\mathrm{A}}{n\,\pi}\,\sin\left(n\,\pi\,\frac{\tau}{T_0}\right)\cos(n\,\omega\,t)\ . \tag{2}$$

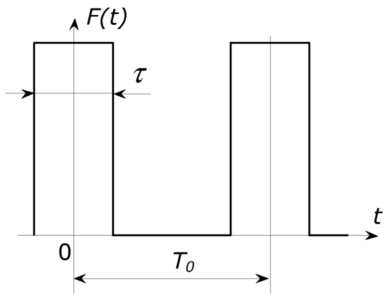

Fig.1: Time function of the rectangular pulses

For a case of 14 electromagnets UTM4 (width 50 mm) distributed on the circle with diameter of 680 mm at speed of 3000 rpm, we get $T_0 = 20/14 = 1.428$ [ms] and $\tau = T_0/3 =$ $= 0.475{\times}10^{-3}$ [s]. Then Fourier's series has a form

$$F(t) = \frac{F_\mathrm{A}}{3} + \sum_{n=1}^{\infty} \frac{2\,F_\mathrm{A}}{n\,\pi}\,\sin\left(n\,\frac{\pi}{3}\right)\cos\left(n\,\omega\,t\right)\ . \tag{3}$$

After substituting the coefficients in (2) we get

$$F(t) = \frac{F_\mathrm{A}}{3} + \frac{F_\mathrm{A}}{\pi}\left[\sqrt{3}\,\cos(\omega\,t) + \frac{\sqrt{3}}{2}\,\cos(2\,\omega\,t) - \frac{\sqrt{3}}{4}\,\cos(4\,\omega\,t) - \dots\right]\ . \tag{4}$$

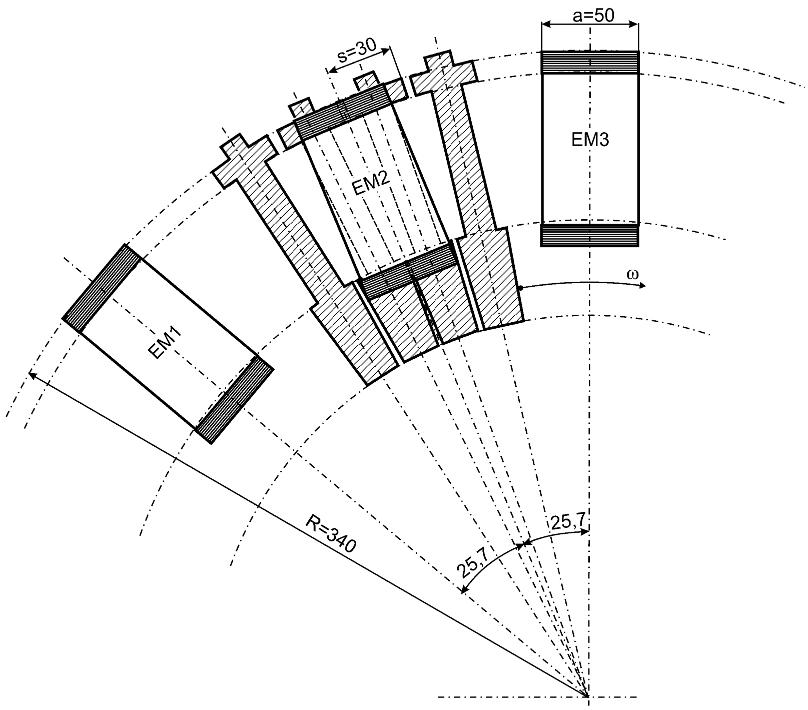

Fig.2: Sketch of the 14-electromagnet set-up around the bladed wheel

The coefficients of the series are zeros for $n = 3\,k$ ($k = 1, 2, \ldots, \infty$). Their corresponding frequencies can be obtained from the zero condition $3\,k\,\pi\,\tau/T_0 = i\,2\,\pi$ ($i = 0, 1, \ldots, \infty$) of these coefficients from (2). Then we get $f_i = 2\,i/(3\,\tau)$. The first ($i = 1$) frequency f_1 shows the frequency span of the pulse electromagnet excitation and for the case of UTM4 it is 1435 Hz. The consequences of the Fourier's analysis are: a) by increasing the electromagnet number the period T_0 proportionally decreases and the amplitudes of spectral components proportionally increase; b) by decreasing the width of electromagnets τ at the same electromagnet number the amplitude A proportionally decreases but zero frequency becomes proportionally higher.

Force amplitude of the pulses can be expressed approximately by the relation

$$F_{\mathrm{A}} = \frac{1}{2\,\mu_0}\,B^2\,S\;, \tag{5}$$

where B is the magnetic induction in the gap, μ_0 permeability of vacuum, S intersection of areas of electromagnetic poles and the passing blade.

3. Design of excitation method of rotating blades

Sufficient excitation of stiff and damped rotating blades requires a distribution of a higher number of electromagnets along the circumference of the wheel in a stator space. The design of the distribution and synchronization comes from the assumption that the blade vibrates by its eigenmode e.g. $y = a\,\sin\omega t$ and rotates with an angular speed Ω. The resonance vibration can be achieved by synchronizing the eigen-vibration of the blade with excitation pulses. The necessary condition is that the ratio between period of excitation pulses T_0 and period of eigen-vibration T_{R} is equal to integer number analogically to (1). Furthermore, pulses of the electromagnet must arise when the blades pass the electromagnet and its attractive force acts on the blade when the velocity of the blade vibration starts to have the same direction as the force.

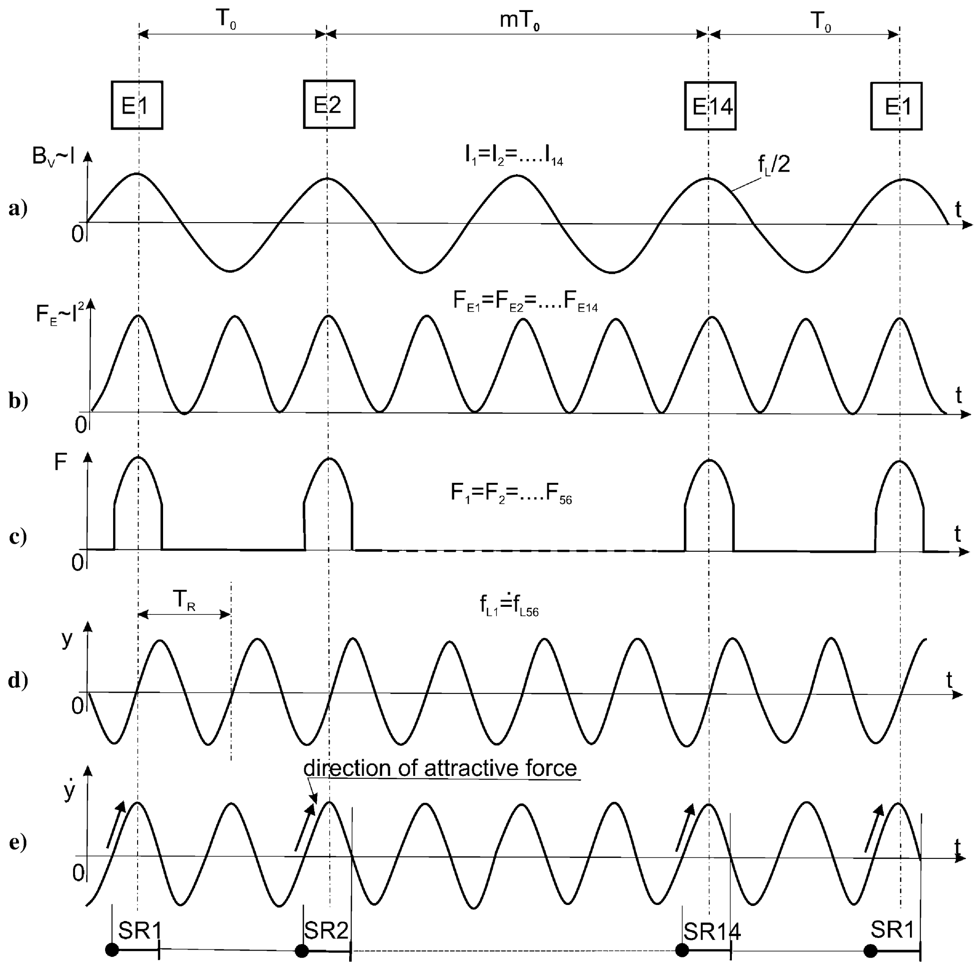

Fig.3: Synchronization of excitation for resonance vibration of bladed wheel

An example of the excitation synchronization for a resonance vibration is shown in Fig. 3. Electromagnets are supplied by the currents I of the same amplitude, phase and excitation frequency (a). The time dependence of the electromagnetic force and pulses acting on the blade are depicted in b) and c) respectively. The displacement and velocity of vibration of the blade are shown in graphs d), e). The appropriate excitation time intervals, depicted as regions of synchronization (SR), are determined for the cases when the velocity has the same direction as the attractive force (see arrows) of electromagnets. It can be met by the following synchronization methods:

a) by revolution speed for setting the integer number of vibration periods during period T_0 (one revolution for one electromagnet or time of blade passage between neighbor electromagnets for multiple electromagnets),

b) for given revolution speed by phase shifts of supplied currents of electromagnets with respect to one chosen reference electromagnet :
   - by the specific values of a serial impedance compensator linked to the electromagnet coil,
   - by phase RC circuits at the amplifier inputs,
   - by the programmable generator signals at the amplifier inputs.

The velocity of the blade vibration can be obtained by the analog shunt circuit from the strain gauge signals of the displacement.

4. Verification of the design on the two electromagnet excitation of test bladed wheel

The test bladed wheel of IT AS CR (Fig. 4) consists of a disc (⌀505 mm) with 60 prismatic blades (6×12.5×190 mm) screwed to its perimeter with zeros pitch angle. The first axial eigenmode frequency of blade in steady non-rotating state is around 143 Hz. Two electromagnets (EM1, EM2) of UTM4 were placed against the tips of blades in angle span 180° on the stator plate. Bladed wheel is driven by the engine with speed controller ranging from 28 up to 1100 rpm. The magnetic field of the electromagnets acts by force pulses on the rotating blades during their passages around the electromagnets. The electromagnet pulses were synchronized by method a).

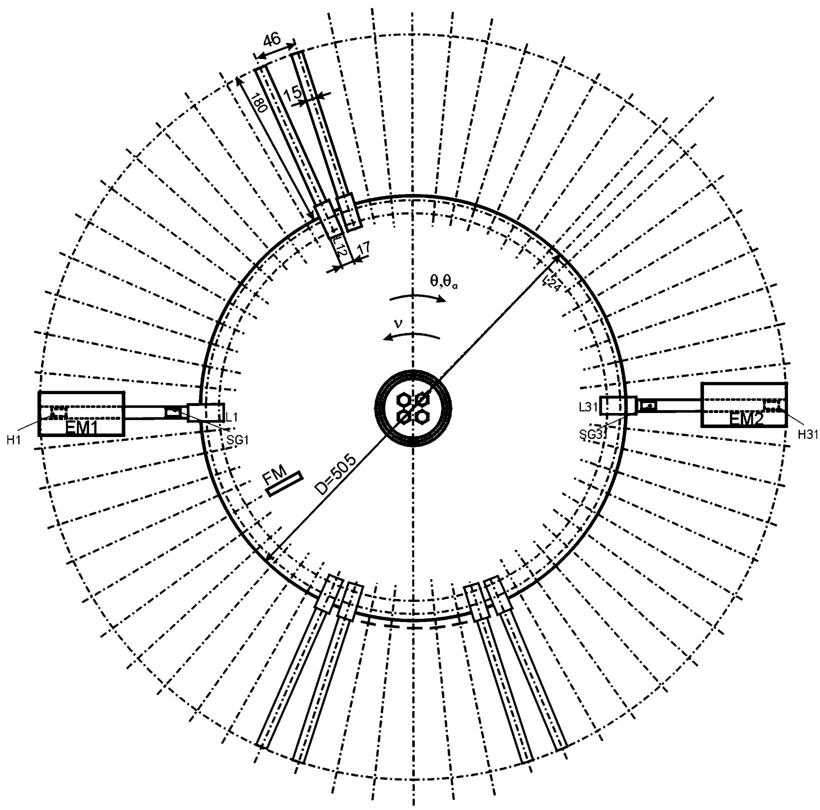

Fig.4: Test wheel of IT AS CR with sensors (hall – H, strain gauge – SG), phase mark FM and electromagnets EM1, EM2

The blade excitation by magnetic field is measured by Halls sensors (H1, H31) placed on the blade L1 and L31 against upper poles of the electromagnets. The excitation force and blade displacement were measured by couples of Si strain-gauges (SG1, SG31) glued at the root of the blades. The amplifiers of output voltage of strain-gauge semi-bridges and Hall's sensors were fixed to the disc of the wheel. The amplified voltages are led via the slip ring Sk12 Hottinger on the digital oscilloscope and on the analyzer BK Pulse 10.0 for recording.

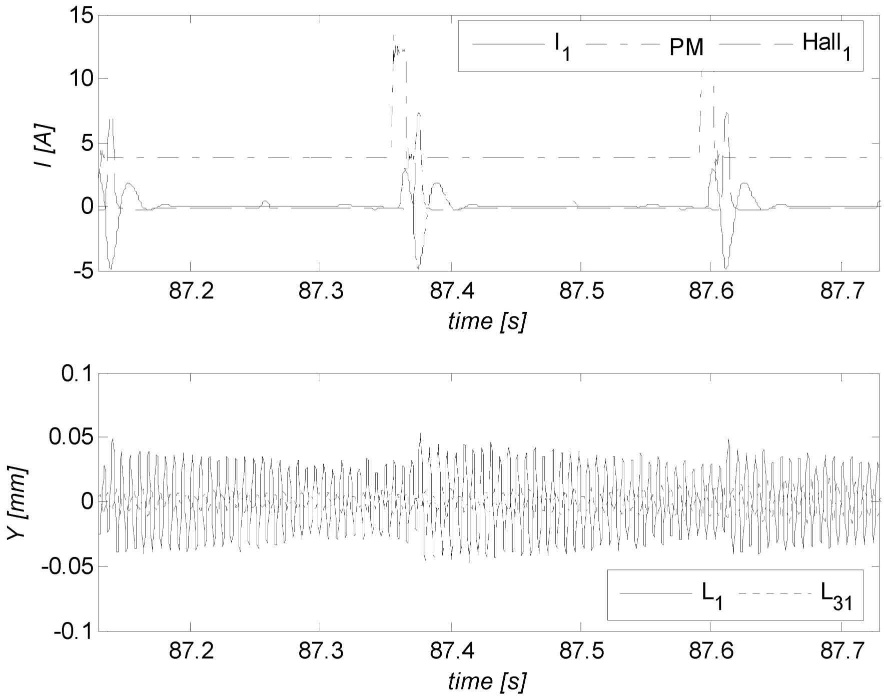

Fig.5: Time characteristics : a) EM1 supply current (solid), FM signal (dash-dot) and Hall sensor signal (dash line); b) displacement of blade L1 (solid), L31 (dash) at supply 5 A and 253 rpm

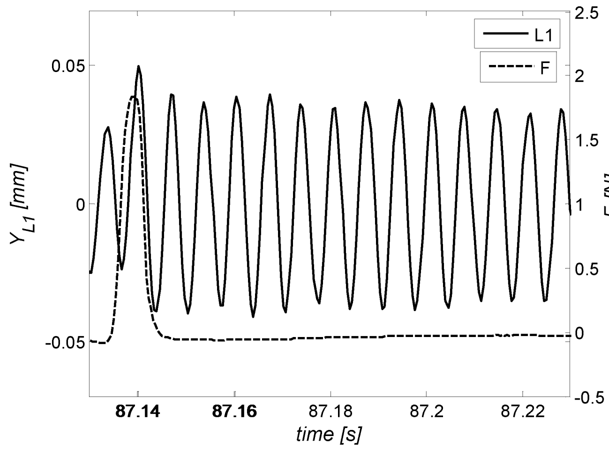

Fig.6: Zoomed time characteristics of displacement of blade L1 and force of EM1 at current supply 5 A and 253 rpm

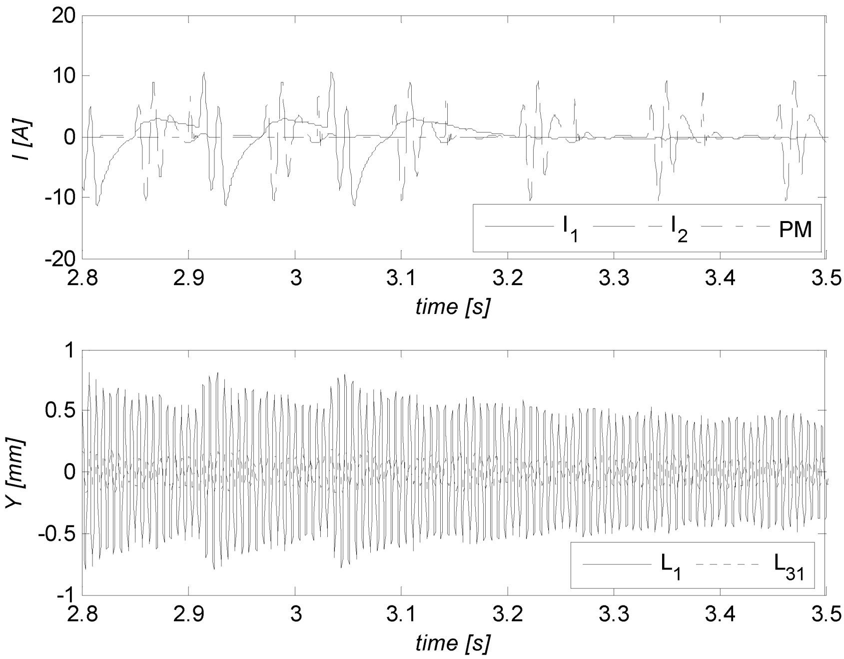

Fig.7: Time characteristics of the first experiment: a) EM1 supply current (solid), EM2 supply current (dash) and FM sensor signal (dash-dot line); b) displacement of blade L1 (solid), L31 (dash) at supply 10 A and 498 rpm

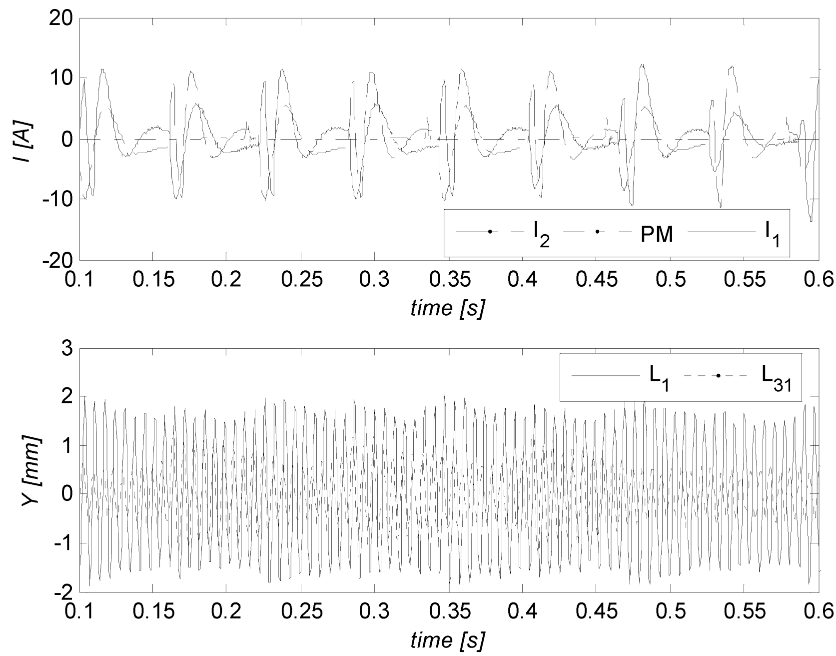

Fig.8: Time characteristics for the other experiment: a) supply current I_1 (solid) of EM1, supply current I_2 (dash) of EM2 and phase mark PM sensor signal (dash-dot line); b) displacement of blade L1 (solid), L31 (dash) at supply 10 A and 498 rpm

An example of time characteristics of the first flexural mode resonance vibration of the blade L1 excitated by one electromagnet EM1 with current supply 5 A and revolution speed 249 rpm is shown in Fig. 5. Since the L31 blade eigenfrequency is 149.4 Hz, the speed corresponds to 36 multiple of the vibration period. Besides displacements of blade L1 and L31 and supply current, signals of the Hall sensor and phase mark are depicted here. The force is proportional to the Hall sensor signal power two. For a better visibility of the synchronization between the displacement of the blade L1 and the electromagnet force their zoomed characteristics are in the Fig. 6. Phase lag 90° between displacement and force pulse shows that the force is in phase with its velocity during the blade passage. Since the blade movement was in the same direction as the attractive force, it is in accordance with requirement for the synchronization (see Fig. 3). Excitation of the disc by two electromagnets EM1, EM2 is shown on two examples by current supply 10 A and revolution speed 498 rpm. The speed 498 corresponds to 9 multiple of the vibration period during passage between the electromagnets. The first experiment was performed for excitation of the blade L1 when the current I_2 of electromagnet EM2 was not accurately synchronized with the L1 blade vibration. A saw-tooth waveform of the L1 response with sharp increase of amplitudes at the moment of blade passage by EM1 can be seen in Fig. 7. At the passage of EM2 the response is much less amplified as it is obvious from the end (time after 3.3 s) of the graph when EM1 was switched off and EM2 worked alone. The other experiment was performed with excitation of two blades (L1 and L31) by both electromagnets (Fig. 8). The synchronization of EM1 and EM2 was set for blade L1 so the saw-tooth waveform with double count per one revolution appeared and displacement level doubled. However, in case of blade L31 excitation, the synchronization was not accurately tuned to the revolution speed and the response was similar to the first experiment. Since the eigenfrequencies of L1 and L31 are slightly mistuned the synchronization by revolution does not work for both blades together. Displacements of blade L1 and L31 and supply currents of EM1 (I_1), EM2 (I_2) and phase mark PM are depicted for these experiments in Fig. 7 and 8.

5. Conclusion

In the contribution the method of excitation of rotating blades by synchronization of multiple electromagnets distributed around the wheel periphery is presented. This method enables to excite arbitrarily selected blade and by synchronization of electromagnets to cumulate its kinetic energy up to steady state resonance vibration. This method can be with merit used for excitation of stiff blades with inter-blade couplings for the dynamic tests of their couplings. The size of poles and impedance of coil of electromagnets must be design according to required amplitudes of the electromagnetic pulses and frequency range of excitation. Using Fourier's series it is shown how the width of pulse and period of pulses influence the amplitude and frequency span of the force. The excitation method for synchronization by revolution speed was verified on the test wheel of IT AS CR at the set up with two electromagnets. The results show the effect of accuracy of the synchronization of the electromagnet pulses with the blade vibration response. Displacement level of blade vibration doubled for proper electromagnet synchronization. The advantage of the speed force synchronizations is in a simple arrangement but the drawback is that the revolution speed can be set only for one selected eigenfrequency. In case of multi blade excitation with blade eigenfrequency mistuning, the force pulses may not be rightly synchronized with movement of all blades. For accurate synchronization the phase shifts of supplied current pulses of electromagnets should be synchronized with the movement of each blade separately.

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