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Rotor blade vibration simulator of steam turbine with aliasing frequencies up to 25 Hz

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Abstract

The tip-timing measurement of rotor blade vibration of a real turbine is very expensive. An electronic simulator of unshrouded steam turbine rotor blade vibrations for aliasing frequencies up to 25 Hz is presented in this paper. The results of the simulated blade vibrations were compared with ones carried out on a real steam turbine. The simulator can be also used to: calibrate the measurement channels, help in the designing and manufacturing new tip-timing systems, and check the reliability of other tip-timing systems.

Keywords: Tip-timing; Rotor blade vibration; Blade vibration simulator

1 Introduction

The experimental determination of rotor blade vibrations is traditionally performed using strain gauges. The practical limitation in the use of strain gauges is that only a few blades in a rotor stage can be measured. An alternate method is the nonintrusive technique of measuring the vibration amplitudes and frequencies of all rotor blades. The first noncontact measurement of rotor blade vibration was

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carried out by Campbell in 1924 [1], who applied induction sensors to identify the natural frequencies of rotating steam turbine blades. A review of literature on noncontact blade vibration measurement is beyond the scope of this paper. Instead, the interested reader may consult Rzadkowski *et al.* [2]. In 1987 Szczepanik and Kudelski [3,4] developed and installed the SAD-2 system (system for analysis vibration of turbine engine bladed disc and rotor) into the first stage compressor of an SO-3 TS-11 Iskra jet engine. This was one of the first airborne tip-timing systems in the world and is still used by the Polish Air Force today. A new tip-timing system for measuring steam turbine blade amplitudes is being developed at the Air Force Institute of Technology in Warsaw and the Szewalski Institute of Fluid-Flow Machinery in Gdańsk. This system consists of a tip-timing simulator of rotor blade vibrations, tip-timing sensor, amplifier, a data acquisition and processing system. The sensor generates analog pulse each time a blade passes in front of them, amplifier increases the values of signal and changes to digital pulse (triggering) that is a rotor blade time of arrival. In data acquisition system an oscilloscope online display of the rotor blade vibration amplitude. The tip-timing sensors record every blades's arrival time and uses the time differences between expected (nonvibrating) and actual arrival times to calculate blade amplitudes. The detailed post run analysis is performed using analyze blade vibration software. The blade vibration simulator generates the blades' times of arrival as they would be registered by a sensor in the turbine casing. The tip-timing measuring system is shown in Figs. 1 and 3, where S_B is the blade sensor, S_R, the rotor sensor, T_B the time of blade arrival, and T_R, the time of one rotor rotation. The simulator could replace the rotor blade vibration signals of sensors mounted in the casings of real aircraft engines or gas and steam turbines (Fig. 2). In the simulator various arbitrary blade amplitudes, phases and frequencies can be applied. This is useful in checking the algorithm of the tip-timing system as well as the measuring channel. The simulator can replace very expensive experiments on real steam turbines rotor blades [5–8]. It is very useful in modelling and developing prototype tip-timing systems. With the simulator one can check the operation and accuracy of any tip-timing system.

2 Analysis of blade vibration using tip-timing technique

The tip-timing method will be used to analyse blade tip amplitudes. Let us assume that the bladed disc consists of K blades (B_1,..., B_K) (Fig. 3). The angle between blades is equal to α. Sensor S_B in the casing provides information about

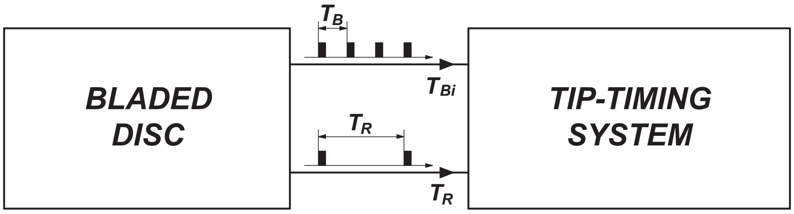

Figure 1: The tip-timing measurement system.

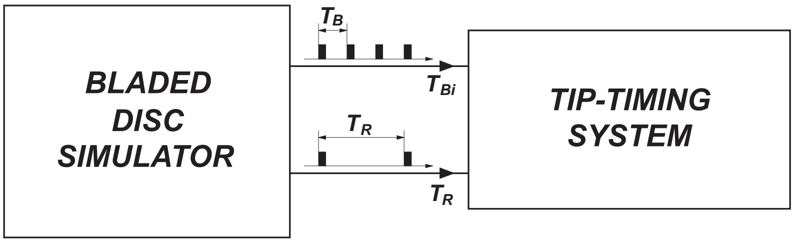

Figure 2: The tip-timing measurement with simulator.

blade tip vibration, while sensor S_R registers rotor rotation, giving one signal per revolution. Figure 4 presents the dependence between signals obtained from blade sensor S_B and rotor sensor S_R. The signal from rotor sensor S_R appears between blade signals B_K and B_1, and starts at 1/2 $T_{(BK-B1)}$. For every blade the T_{B1},T_{B2},. . . , T_{BK} times (Fig. 4) are found. If rotor the blades are not vibrating T_{B1}=...=T_{BK}=T_R, and if they do vibrate, $T_{B1} \neq ... \neq T_{BK} \neq T_R$.

The tip-timing measuring system of rotor blade is presented in Fig. 3. Let us assume that ith rotor blade vibrates in the first mode with f_{Bi} frequency and A_{Bi} amplitude. When the rotor rotation speed is 3000 rpm ($f_R = 50$ Hz), the tip of the blade appears under sensor S_B every 20 ms. The rotation frequency in a steam turbine changes in the $f_R = 50 \pm 0.1$ Hz range. This creates an analogue signal, which is next converted into a digital one (in form of the rectangular bar) when analogue signal crosses zero time.

The blade vibration frequency is higher than the sampling blade frequency ($1/T_R$), so aliasing appears and the blade frequency could be found from

$$f_{Bi} = f_{Boi} + kf_R \ , \tag{1}$$

where f_{Boi} is the ith blade aliasing frequency obtained from the measurement, k is the integer $0, \pm1, \pm2, \ldots$, and f_R is the rotor frequency.

The tip-timing measurement is presented in Fig. 5. When the blades are not vibrating, $T_{Bi} = T_R$, and when they do, $T_{Bi} = T_R \pm A_{Bi}$.

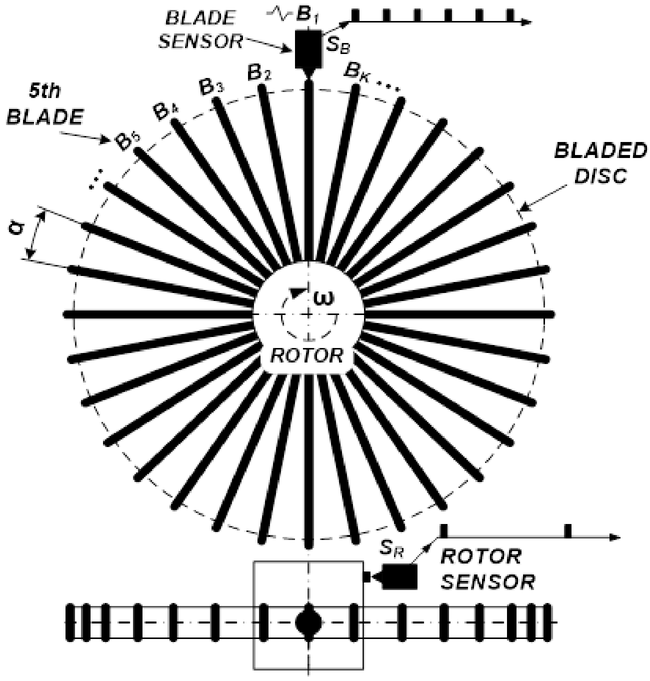

Figure 3: Bladed disc in tip-timing measurement.

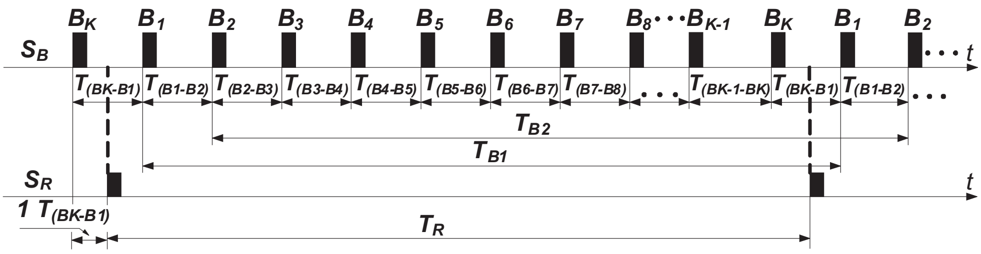

Figure 4: The dependence between signal obtained from sensors S_B and S_R.

The temporary blade vibration period can be found in

$$T_{Bi} = T_R + A_{Bi} \sin(\omega_{Bi} t) \ , \tag{2}$$

where $\omega_{Bi} = 2\pi f_{Bi}$. In order to know T_{Bi}, T_R must be measured independently. This conclusion is very important in the case of changing the rotation speed.

If the amplitude of blade vibration is to be measured with 0.1 mm accuracy, the sampling time must be determined. For example, if rotor rotation

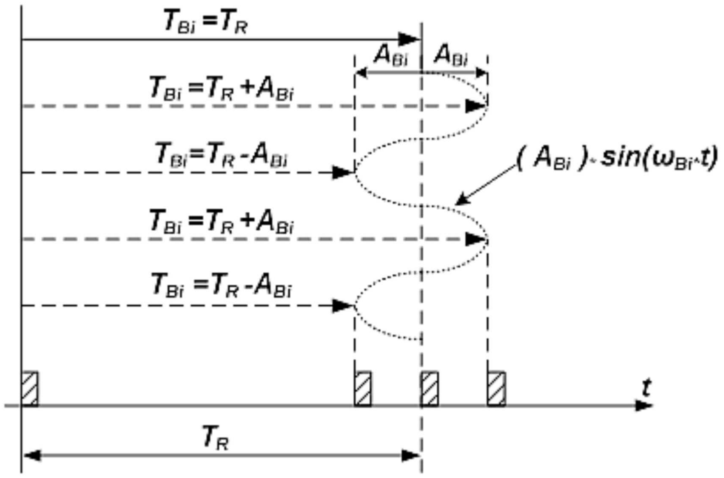

Figure 5: Tip-timing measurement of a vibrating blade.

speed is 3000 rpm ($f_R = 50$ Hz, $T_R = 20$ ms) and the radius of the rotor and blade is $R_R = 1.59$ m, then the circumference blade tip motion is $S = 2\pi R_R = 10$(m)(10 000 mm). To obtain 0.1 mm accuracy, circumference $S = 2\pi R_W$ must be divided by 0.1 to provide number of segments $N = 10\,000/0.1 = 100\,000$. The temporary resolution is $\Delta t = T_R/N = 200$ ns, and the frequency of the reference generator (clock for data acquisition) is $f_a = 1/\Delta t = 5$ MHz.

Figure 6 shows the interdependence between Δt measurement accuracy in period T_R and ΔS blade tip movement. The interdependence between N, T_R and Δt is expressed as

$$N = \frac{T_R}{\Delta t} = \frac{\frac{1}{f_R}}{\frac{1}{f_a}} = \frac{f_a}{f_R} \, , \tag{3}$$

where N is the number of segments, T_R the time of one rotor rotation, $\Delta t = t_a$ the sampling period and f_R the frequency of one rotor rotation. Number N gives information about the resolution of blade tip ΔS vibration amplitude

$$\Delta S = \frac{S}{N} = \frac{2\pi R_R}{N} = \frac{2\pi R_R f_R}{f_a} \, , \tag{4}$$

where R_R is the radius of blade and rotor, f_R the frequency of rotor rotation and $f_a = 1/\Delta t$.

Table 1 presents blade amplitude resolution ΔS in relation to f_a frequency. When $f_a = 5$ MHz, we have one impulse for 0.1 mm, and when $f_a = 80$ MHz, we

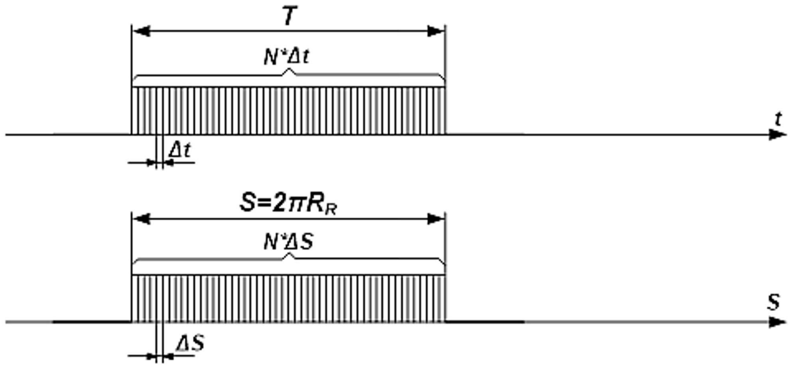

Figure 6: Resolution of measurement.

have 16 impulses for 0.1 mm. The results are presented also for 0.2 mm, 0.5 mm, and 1 mm.

Table 1: Blade amplitude resolution ΔS in relation to f_a frequency (clock for data acquisition).

$f_R = 50$ Hz $R_R = 1.59$ m $S = 2\pi R_R = 10$ m ΔS [μm]	Impulse number $N_{0.1mm}$	Impulse number $N_{0.2\mathrm{mm}}$	Impulse number $N_{0.5\mathrm{mm}}$	Impulse number $N_{1.0\mathrm{mm}}$	f_a [Hz]	$N = f_a/f_R$
6.25	16	32	80	160	80 000 000	1 600 000
12.50	8	16	40	80	40 000 000	800 000
25.00	4	8	20	40	20 000 000	400 000
50.00	2	4	10	20	10 000 000	200 000
100.00	1	2	5	10	5 000 000	100 000
250.00	–	1	2	4	2 000 000	40 000
500.00	–	–	1	2	1 000 000	20 000

3 Rotor blade simulator up to 25 Hz

The vibration of blades in a bladed disc are simulated. When ith blade passes sensor S_B, the time of blade arrival is measured. The time of arrival indicates the blade vibration. In order to model correctly the blade vibration, we start by creating the time of arrival of nonvibrating blades, where $T_{Bi} = T_R$ (see Fig. 4). Thus the geometrical mesh is created for every nonvibrating blade as the base of the simulator, and this mesh models the nonvibrating bladed disc. Blade vibrations are next superimposed onto this mesh (see Fig. 5).

Time of blade arrivals can be measured blade to blade $T_{(BK-B1)}$, $T_{(B1-B2)}$,..., $T_{(B(K-1)-BK)}$ (Fig. 4) and once these measurements are completed, the T_{Bi} of individual blades can be calculated. Alternatively $T_{B1}, \ldots, T_{BK}$ are established after every rotation (Fig. 4). The latter method was applied in the blade vibration simulator presented in this paper.

In our simulation the bladed disc rotated at 3000 rpm (50 Hz). The blade vibration frequency was higher than the sampling blade frequency ($1/T_R$), so aliasing appeared and the blade frequency could be found from Eq. (1). Figure 7 presents the time of measurements of particular blades excited by simulator. The upper line presents the reference rotor signal (one signal per revolution), and the lower lines the blade signals. Only one vibrating blade was assumed, represented by two lines close to each other (lower lines), with the nonvibrating blades represented by a single line. Figure 8 presents the real vibrations of a last stage low pressure steam turbine rotor blade. The multitude of bars (A [V]) is due to blade vibration which is not synchronized with the sampling frequency. Figure 9 presents vibration of particular blade excited by simulator, represented by two lines ($+A$ [μs] and $-A$ [μs]). The comparison between experimental blade amplitude and simulator blade amplitude is satisfactory.

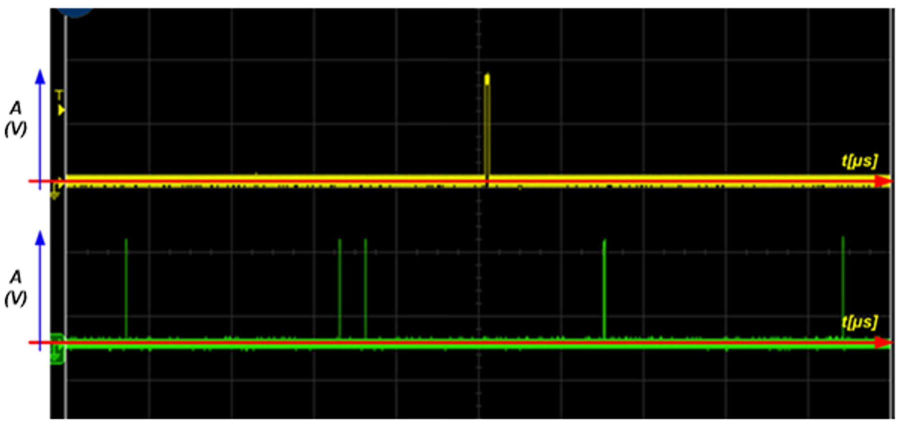

Figure 7: Blade vibration modeled by simulator.

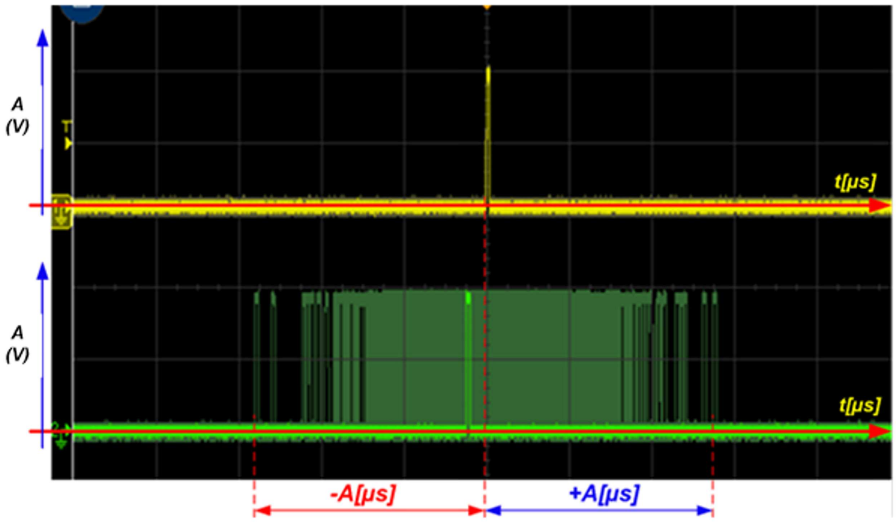

Figure 8: Rotor blade vibration in real steam turbine.

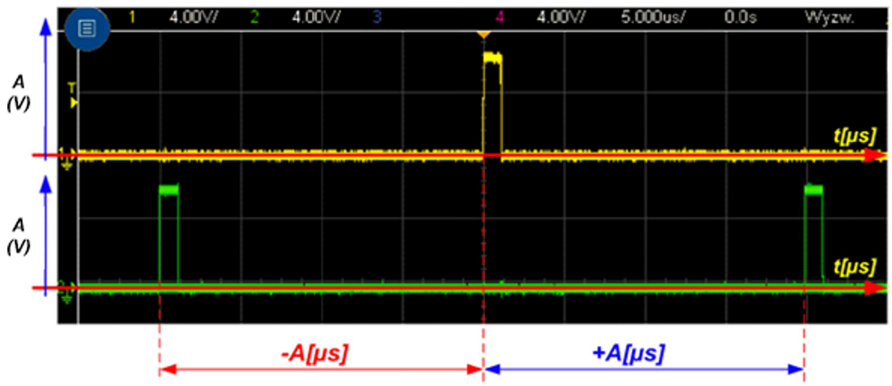

Figure 9: Rotor blade vibration in real steam turbine modeled by simulator.

4 Conclusions

In this paper a simulator of unshrouded bladed discs based the general concepts of tip-timing measurement was presented. An experiment of measuring aliasing frequencies up to 25 Hz (3000 rpm) was described. The simulated blade vibration results were compared with the ones of a real steam turbine. The comparison is satisfactory. The simulator already now can be used to calibrate measurement channels, help design new tip-timing systems and check the accuracy of other tip-timing systems.

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