USE OF MECHANICAL RESONANCE IN MACHINES DRIVE SYSTEMS

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In this article the use of mechanical resonance in the drive systems of impact working machines and in machines with crankshaft systems will be discussed. The total mechanical energy and the vibration amplitude of the mass in an oscillator at resonance are increasing to certain values, which are dependent on damping. In steady state conditions at resonance, the delivered energy is equal to the energy dissipated in the oscillator. During resonance and due to the amplification of the vibration amplitude, energy in the oscillator will be accumulated. The accumulation of energy is similar to that in a flywheel. A possibility of sequential energy extraction from mechanical resonance and its application on the example of a punching press has been presented. In a machine with a crankshaft drive system the resonance lead to the reduction of torque amplitudes in the drive systems, similar like flywheels.
Keywords: vibration, mechanical resonance, machine drives

1. Introduction

The vibration amplitude of a mechanical system depends on the ratio of the driving force frequency and the natural frequency of the system. When the excitation force frequency is equal to the natural frequency of the object, the phenomenon of mechanical resonance occurs, and as a result strong increases in the vibration amplitude can be observed [1- 4]. Assuming, theoretically, that energy dissipation is present in any mechanical system due to the damping, the amplitude of vibration cannot increase in the state of resonance above a certain value.

Resonance in mechanical systems is in most cases unwanted. Increased vibrations are connected with accelerations and thus with dynamic loads acting on the components of the systems. Overload and fatigue may strongly influence the integrity of a construction or structure e.g. the Tacoma Bridge, footbridges, shaft critical speeds, etc.

There are many papers concerning energy use from mechanical resonance [5 - 11]. Scavenging of vibration energy is used in microscale to power small onboard devices, sensors and electronics. The intentional use of mechanical resonance can be found in micro-scale systems – MEMS [8]. The transduction of vibration energy may occur in a mechanical or electromagnetic way, e.g. a DC generator. Large-scale energy harvesting has been described in [9-12]. Vibration energy may be harvestable in vehicle suspension systems, from the vibration of buildings and railway tracks, from human motion and from ocean waves etc. It has been stated that the most efficient energy harvesting occurs at the resonance conditions of the harvester [7, 13]. The paper [5] presents the case of a robotic arm where, due to the use of resonance, energy savings up to 56 % were achieved.

The positive effects resulting from mechanical resonance are also used in the development of the optimal parameters of micro-propulsion systems to drive flying objects using the movement of wings [5]. Among other applications resonance is used in vibratory conveyors and in resonance drilling machines. There is a very significant increase in the energy efficiency of such machines using resonance phenomena [10, 12].

The main purpose of this paper is to analyse the energy accumulation in a mechanical resonance an its use in drive systems of machines. Based on simulation and experimental investigations, the sequential extraction of energy from an oscillator in resonance has been described. Finally, the accumulation of energy at resonance and its use in a prototype of punching press machine and in the crankshaft system was presented.

2. Oscillator and flywheel

The literature presents many descriptions and investigations regarding the phenomenon of resonance [1-5]. A simple description of mechanical resonance is presented in the example of the mechanical oscillator shown in Fig.1.

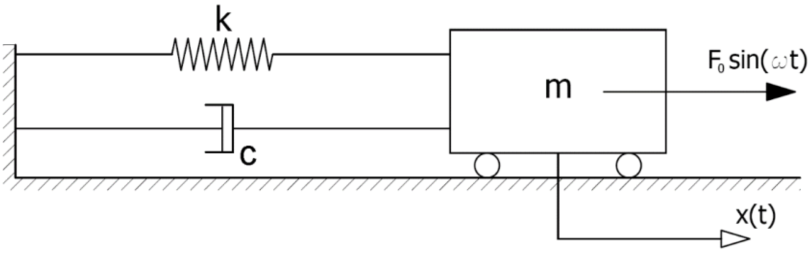

Figure 1. Forced vibration of a damped mechanical oscillator.

The amplitude of oscillation can be defined as:

$$A = \frac{\alpha_0}{\sqrt{\left(\omega_d^2 - \omega^2\right)^2 + 4\beta^2\omega^2}} \tag{1}$$

where:

$$\beta = \frac{c}{2m},\ \ \omega_0 = \sqrt{\frac{k}{m}},\ \alpha_0 = \frac{F_0}{m} \tag{2}$$

At resonance when $\omega = \omega_d$ the oscillation amplitude reaches the maximum value. For a damped mechanical oscillator the maximal amplitude in resonance is defined by:

$$A_{max} = \frac{\alpha_0}{2\beta\omega_d} \tag{3}$$

The excitation force is shifted ahead in the phase by $\frac{\pi}{2}$ to the displacement of the oscillator.
The natural frequency of a damped system is defined by:

$$\omega_d = \sqrt{\omega_0^2 - 4\beta^2} \tag{4}$$

The kinetic energy in the oscillator is defined as

$$KE = \frac{m\dot{x}^2}{2} \tag{5}$$

potential energy as

$$PE = \frac{kx^2}{2} \tag{6}$$

and the total mechanical energy

$$TE = \frac{kA^2}{2} \tag{7}$$

Fig. 2 presents the time courses of forces acting in the oscillator at a steady state in resonance. It can be seen that the sum of the inertia force and the spring force at resonance is equal to 0 because they have the same amplitude and are shifted in phase at 180 °. The excitation force, which is usually several times smaller than the inertia and spring forces, is used to overcome the damping force only.

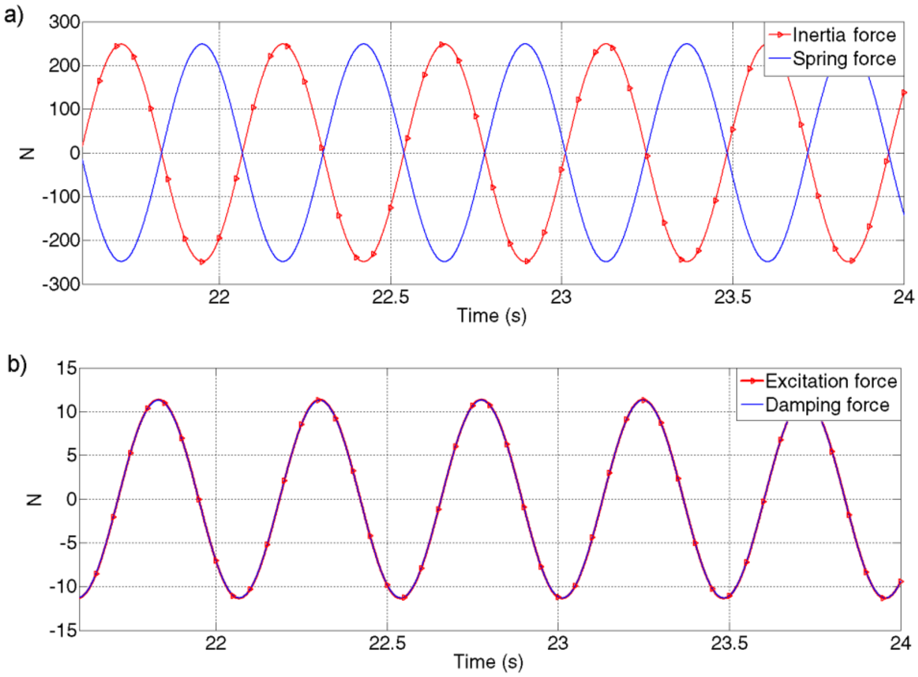

Figure 2. Mechanical oscillator - comparison of forces in the oscillator at resonance:
a) inertial and spring forces, b) excitation and damping forces.

In steady state conditions of resonance, the average energy absorbed by the oscillator in a single period of oscillation is equal to the dissipated energy due to damping.

$$E_{dis} = cX^2\omega_d^2 \int_0^T cos^2\,(\omega_d t - \theta)dt = \pi c\omega_d A_{max}^2 \tag{8}$$

The energy accumulated in resonance is then equal to the sum of the potential and kinetic energy of the oscillator:

$$E_{ac} = \frac{1}{2}kA_{max}^2 = \frac{1}{2}m\omega_d^2 A_{max}^2 \tag{9}$$

The ratio of accumulated and dissipated energy can then be defined as:

$$\frac{E_{ac}}{E_{dis}} = \frac{m\omega_d}{2\pi c} = \frac{Q}{2\pi} \tag{10}$$

where Q is the quality factor, which represents the ratio of stored and dissipated energy in an oscillator [1, 3].

From Eq. (10) it can be stated that the ratio of accumulated to dissipated energy increases when the mass and natural frequency of the oscillator increases. With the decrease of the damping coefficient, the ratio of accumulated and dissipated energy increases. The energy accumulated in an oscillator at resonance in steady state conditions, is several times higher than the energy dissipated.

In the flywheel the kinetic energy will be, assuming the influence of mass only of the external ring defined as (Fig. 3):

$$E_{kfw} = \frac{1}{2}I\omega^2 = \frac{1}{2}m\omega^2 r^2 \tag{11}$$

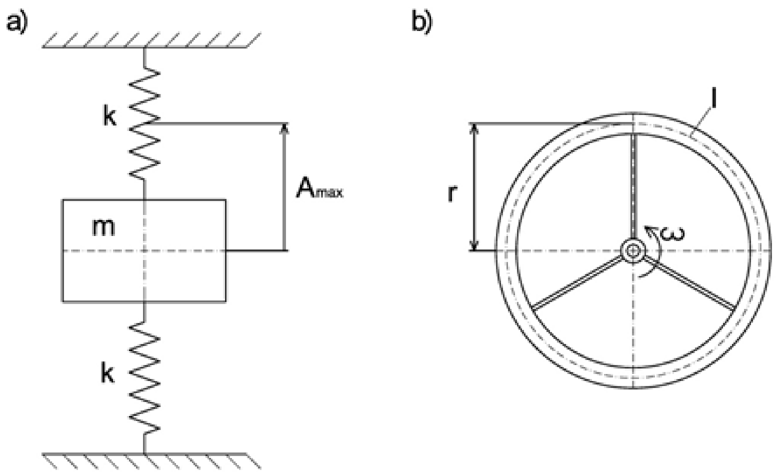

Figure 3. Oscillator and flywheel.

From equations (9) and (11) it can be seen that the energy of the flywheel is equal to the energy of the oscillator when $r = A_{max}$, assuming that the masses of both objects are equal and the angular frequency of the wheel is equal to the natural frequency of the oscillator. The average energy applied to the oscillator in resonance at steady state conditions is equal to the energy dissipated due to damping and is several times lower than the energy accumulated in the oscillator, as shown in Fig.4. In the case of the flywheel the energy applied to the system is equal to the kinetic energy of the flywheel. From Fig. 4 it can be seen that the oscillator energy rises faster than the energy of the flywheel and also takes higher values until the time point t_0 where the oscillator and flywheel energy is equal.

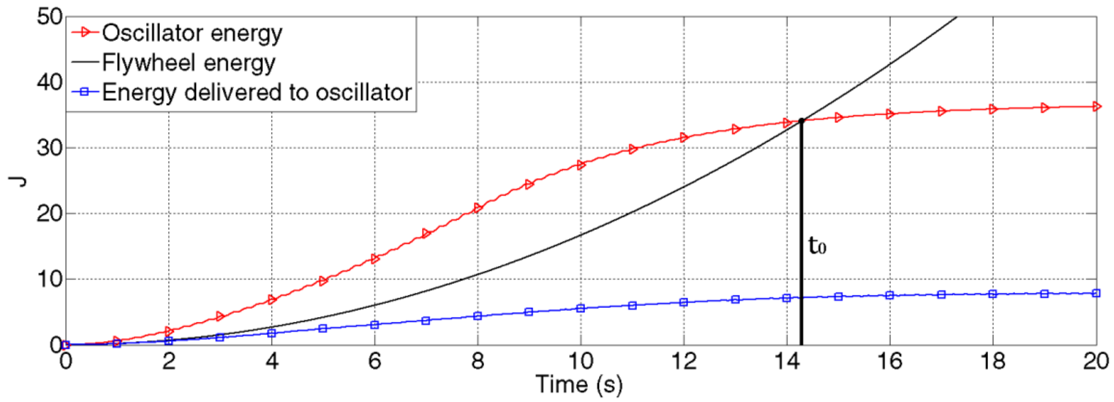

Figure 4. Energy comparison: Oscillator vs Flywheel.

From Fig. 4 can be also stated that the average value of energy delivered to the oscillator at resonance is several times smaller than the energy accumulated in an oscillator. In case of the flywheel it is necessary to perform work to overcome the inertia forces of the flywheel. In the mechanical oscillator at resonance, the inertia forces are balanced by the forces generated due to the springs. The energy delivered to the oscillator at resonance is equal the energy lost due to the damping.

3. Application examples

3.1 Impact working machines

The energy accumulation at resonance can be used in drive systems of impact working machines in similar way as flywheels. Flywheels are used in eccentric mechanical presses to accumulate the energy needed to conduct punching operations. The flywheel is mounted on the drive shaft of the press and its kinetic energy increases with the square of the angular velocity.

Fig. 5 presents the schematic 3D model and view of a prototype of mechanical press with an oscillator unit. The oscillator unit (4) is excited with the resonance frequency with use of rotational mass (9). The electric motor (1) is connected to a gearbox (2) where the rotational velocity is reduced. The work operation of the punching tool connected to the resonance block will be performed using the energy accumulated in the oscillator. The work sequence at the resonance is activated at the point of maximum kinetic energy. The oscillator mass is connected to the punch element via a controlled clutch (8), which is only engaged during the punching action. The clutch is turned on or off with use of the punch clutch triggers (7). It is also crucial that the amplitude of oscillations after the work sequence does not decrease under a certain value. The energy consumption in such drive is smaller in comparison to conventional drives because at resonance the inertia forces are balanced by the spring forces. The energy is needed only to the punching process and to overcome the damping. In case of eccentric presses there are significant more energy losses inside the machine.

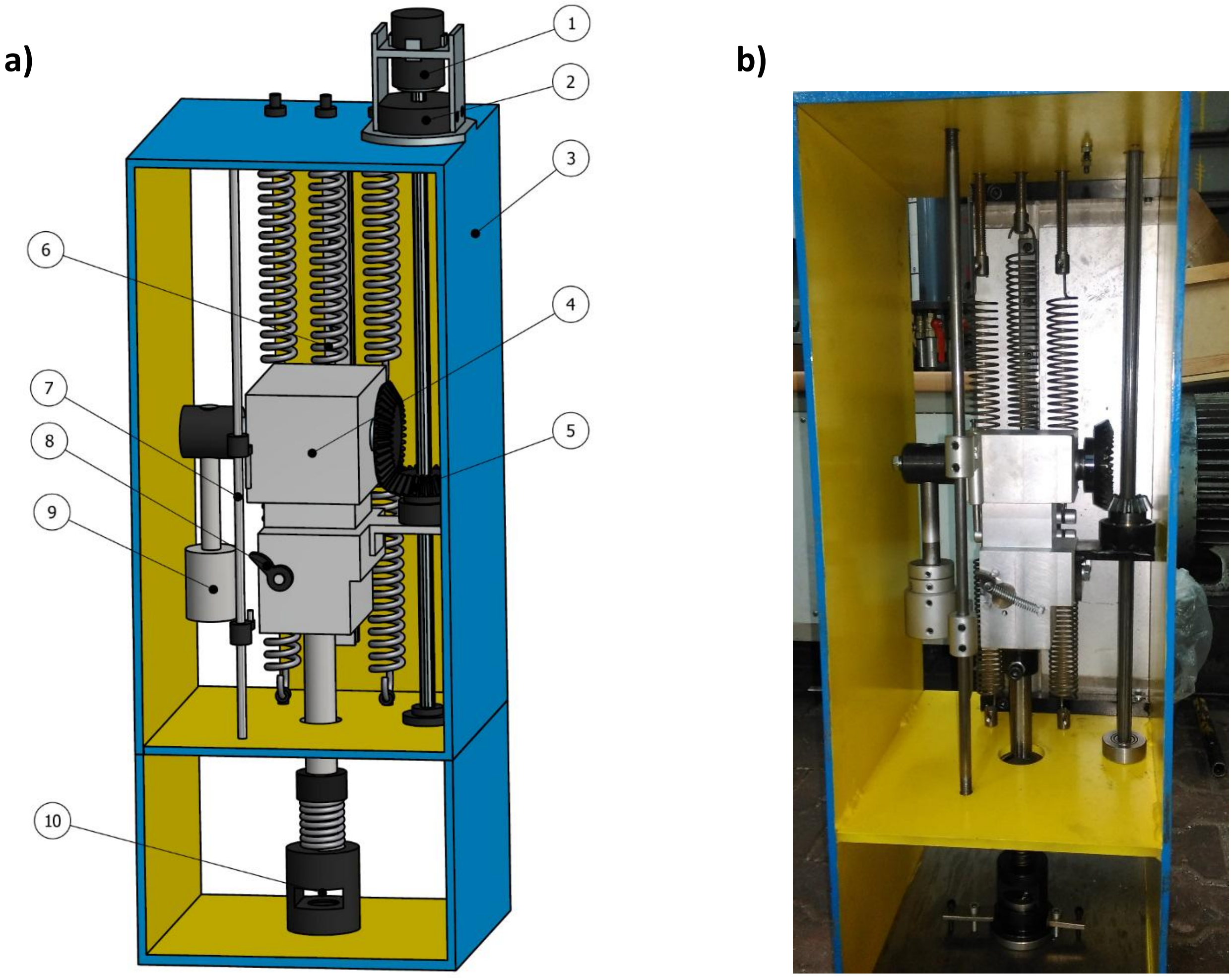

Figure 5. Prototype solution of the punching machine a) 3D model: 1-electric motor, 2-gearbox, 3-housing, 4 – oscillator mass, 5-bevel gears, 6- set of springs, 7- punch clutch triggers, 8- clutch engage switch, 9- rotational mass, 10- punch, b) photo.

3.2 Machines with crankshaft systems

In Figure 6 the schematic view of the crankshaft system with and without attached spring element will be shown. In the case of the crankshaft with a spring, the dynamical force resulting from the inertia, spring and damping acting in x-direction is given by:

$$F_x = m\ddot{x} + c\dot{x} + kx \tag{12}$$

For the crankshaft without a spring, the dynamical force is given by:

$$F_x = m\ddot{x} + c\dot{x} \tag{13}$$

Displacement x of the mass m is related to the angular velocity ω with the following equation:

$$x = r(1 + \frac{\lambda \sin^2 \omega t}{2} - \cos \omega t) \tag{14}$$

The torque on the crankshaft will be established based on the tangential force from the following equation:

$$M = F_x \cdot r \cdot \sin(\omega t + \beta) / \cos \beta \tag{15}$$

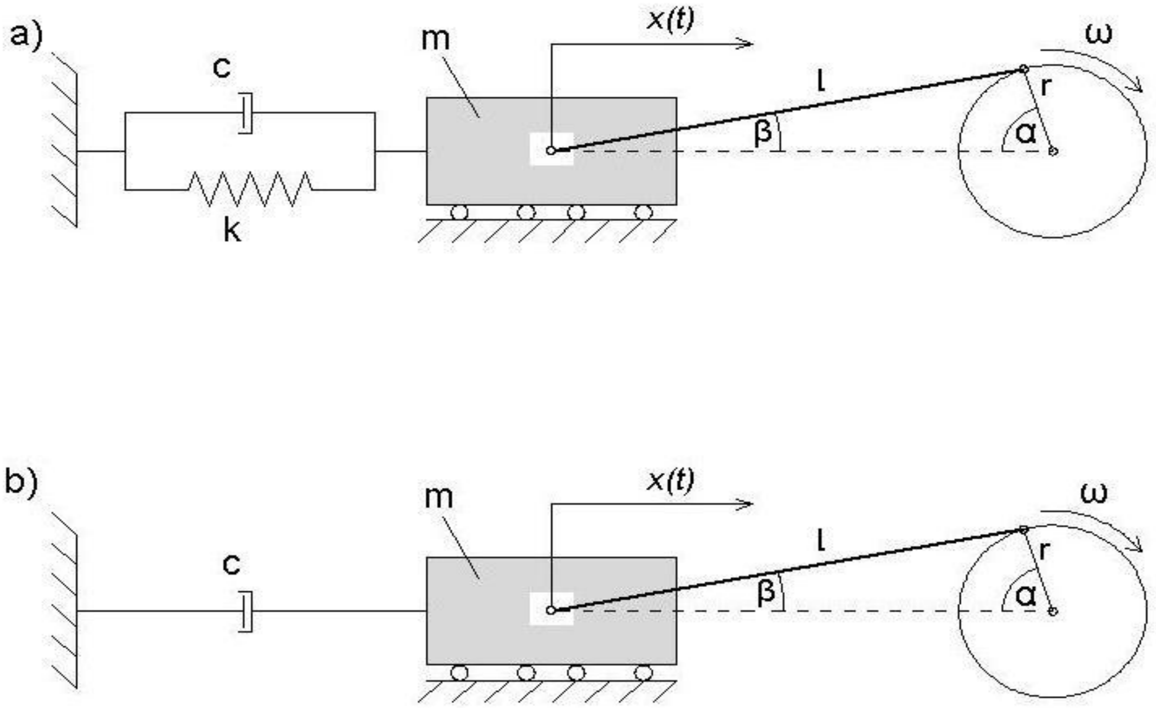

Figure 6. Schematic view of: a) crankshaft with a spring, b) crankshaft without a spring

Figure 7 presents the schematic view of the physical model in which both crankshaft systems were investigated. The physical model consists of the oscillating mass connected with the crankshaft system and with the set of 4 springs. The rpm of the AC asynchronous motor was controlled with the frequency inverter. The force in the crankshaft was measured with the force sensor and the displacement with the laser vibrometer. The mass is mounted on a low friction slide.

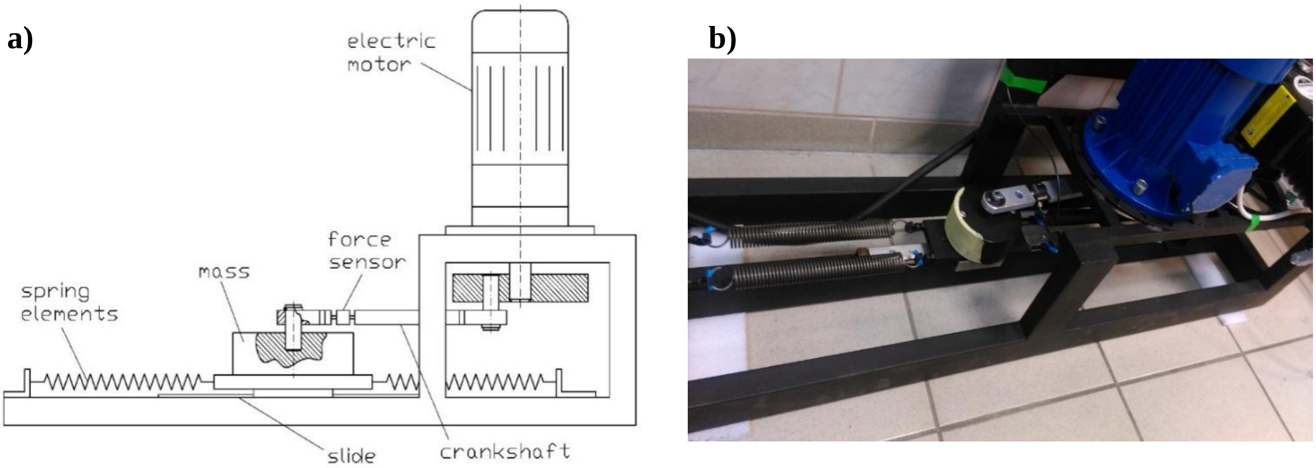

Figure 7. Crankshaft systems: a) schematic view off the test bench, b) photo

In Fig. 8 the measured time courses of the displacement of the mass and the force in the crankshaft is shown. It can be seen that the amplitudes of the force in the crankshaft with spring is decreasing with the increasing of rpm and at the resonance have the minimum value. At resonance, the inertial force of the mass is compensated by the spring force and the driving force is needed to overcome the friction force only. That lead to the reduction of the torque amplitudes in the drive system. By the crankshaft without spring the steady increasing of the amplitudes of the force in the crankshaft is to observe, mainly due to the inertial and friction forces.

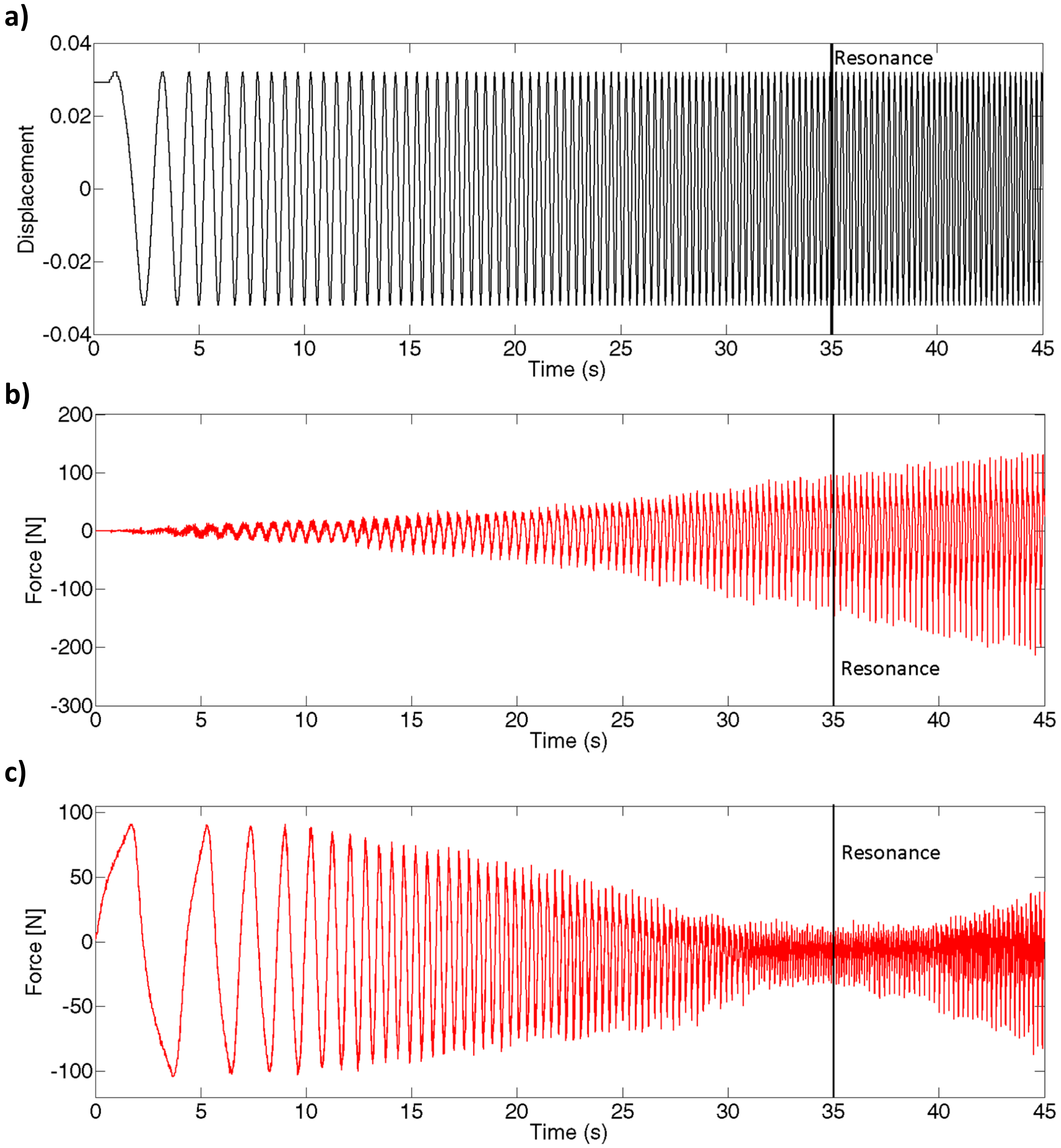

Figure 8. Measured time courses: a) displacement of the mass, b) force without the spring, c) force with the spring

4. Conclusions

Comparing the energy in an oscillator, both in simulation and experiments, leads to the following conclusions. At a steady state of resonance, the total energy absorbed by the oscillating mass is equal to the energy lost due to damping. The energy will be accumulated in the oscillator, as in the case of the flywheel, and can be several times higher than the energy delivered continuously to the system. During the sequential extraction of energy from an oscillator, the excitation forces, usually with relatively low amplitudes, will be transformed into force impulses with high amplitudes. The amplitude of force impulses and the mechanical power gained from the oscillator at resonance is mainly dependent on the damping ratio and frequency. The results presented in this paper can be very useful in a lot of applications, especially in impact working machines. In impact working machines without an accumulation of energy, a relatively high power of the drive for the impulse load forces is required. When using force impulses extracted from an oscillator in resonance, the power of the driving unit can be significantly reduced.

The resonance has also a positive influence in crankshaft systems and lead to the significant reduction of torque amplitudes on the drive shafts of the electric motors.

Further investigations will be focused on the optimization of the parameters of the described resonance drives and of their energy efficiency.

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