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AUTORESONANT EXCITATION AND CONTROL OF NONLINEAR VIBRATION MODES

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Abstract

An approach has been developed to design the resonant vibratory equipment for accomplishment of strongly nonlinear dynamic processes as the self-sustaining oscillating systems using the electronic and electromechanical positive feedback and a synchronous type actuator for self-excitation of resonant vibration in combination with a negative feedback for its stabilisation. Dynamics and control strategies of the autoresonant systems were thoroughly investigated and the results of analysis, design and experimentation with recently developed engineering systems are presented.

Key words

nonlinear dynamics, vibration control, autoresonance

1 Introduction

An effective use of resonant phenomena in physics and engineering demands an increase in quality of vibrating systems. However, an increase in quality leads to the appearance of control difficulties in monitoring the fine resonant tuning. This is because of the strong sensitivity of resonant tuning to parameter and structural deviations. The problem of a fine resonant control is drastically complicated when nonlinear factors, unpredictable variable loads or limited excitation forces produced by the source of energy take place.

An approach has been developed to design resonant vibratory equipment as self-sustaining oscillating systems using electronic and electromechanical positive feedback and a synchronous type actuator for self-excitation of resonant vibration in combination with negative feedback for its stabilisation. This method of control is known as *autoresonant* [Babitsky, 1995; Babitsky, 1998] and uses the term introduced by A.A.Andronov for "…a resonance under action of the force produced by the system's motion." [Andronov, Vitt, Khaikyn, 1966].

The control described transforms the nonlinear system into *homeostat,* which keeps the resonant mode of functioning under wide deviation of ill-defined processing loads.

The autoresonant control provides the possibility of self-tuning and self-adaptation mechanisms for the system to keep the resonant mode of oscillation under variation of its structure and parameters. The implementations of autoresonant control for the new nonlinear vibratory systems are described. These are a screening machine for vibro-impact transportation and separation of drilling mud [Babitsky, Sokolov, 2007] and an ultrasonically assisted cutting machine [Astashev, Babitsky, 2007; Babitsky, Astashev, 2007]. Implementation of autoresonant control allows simple program regulation of intensity of the process in these systems whilst keeping maximum efficiency at all times even for high Q-factor systems. Transient processes keep the resonant efficiency as well.

Dynamics and control strategies of the autoresonant systems were thoroughly investigated and the results of analysis, design and experimentation of recently developed engineering systems are presented.

The opportunity of application of the robust and high quality nonlinear resonant system under wide deviation of processing loads results in essential increase of productivity, efficiency and improvement of design.

2 Autoresonant excitation

The traditional amplitude-*frequency* characteristics represent only one projection of 3-D amplitude-frequency-phase curves that describes stationary forced vibration. The example of the 3-D curve and its projection for an impact oscillator with one limiter (Figure 1) is shown in Figure 2. This figure shows that the amplitude-*phase* curve is single-valued and gently sloping near the resonance unlike amplitude-*frequency* and *phase*-frequency characteristics. This takes place for a wide range of vibrating systems [Sokolov, Babitsky, 2001]. Autoresonant excitation is based on these properties of amplitude-phase curves. Contrary to the forced excitation with prescribed frequency, the autoresonant excitation forms the exciting force by means of positive feedback based on transformation of the displacement (velocity, acceleration) signal [Babitsky, 1995]. The feedback in its simplest form (Figure 3) shifts the phase of the vibration signal from the sensor and amplifies its power. This powerful signal feeds the synchronous actuator, which transforms it to the exciting force. The positive feedback loop also contains an additional mechanism for limiting of excitation force. A level of limitation is controlled by a negative feedback.

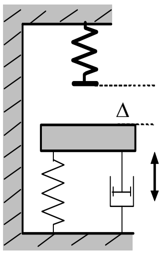

Figure 1. Impact oscillator

Autoresonant system does not have a prescribed frequency of excitation. The frequency and the amplitude of vibration are determined by parameters of the electro-mechanical system and feedback. Parameters of self-sustaining vibration can be controlled by changing the phase shift or/and the limitation level in the feedback circuit [Astashev, Babitsky, 2007; Babitsky, Sokolov, 2007].

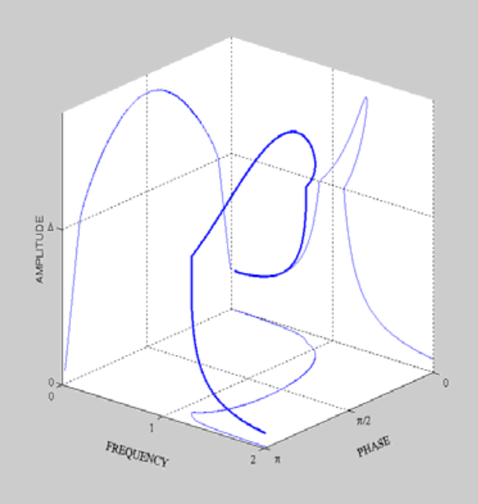

Figure 2. Amplitude-frequency-phase characteristics and its projections.

If we consider self-sustaining vibration of a linear single-degree-of-freedom vibratory system with phase control, it is obvious that the resonant regime takes place when the force is in phase with vibration velocity (or lags 3π/2 in phase from vibratory displacement).

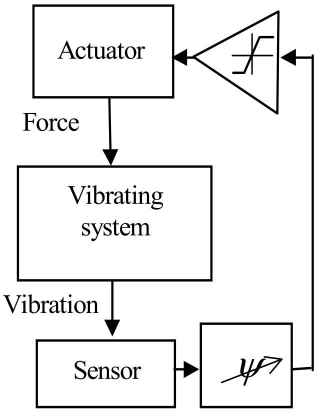

Figure 3. General structure of autoresonant system.

This system is designated as an *autoresonant* one. It keeps the resonant regime of oscillation when the natural frequency of a mechanical subsystem changes. Due to the specific properties of the amplitude-phase curves, the resonant vibration is stable under autoresonant excitation and such a system does not need precise tuning of the phase shift to maintain a resonant regime, in contrast to the traditional forced excitation with frequency control.

Usually we do not need a strictly sinusoidal force to excite resonant vibration due to the strong filtering ability of the vibrating system near resonance. This is especially important in those autoresonant systems where vibration itself is non-harmonic and in powerful systems where it is usually difficult to obtain harmonic force. Any shape of excitation with a pronounced fundamental harmonic is appropriate in autoresonant systems.

3 Applications

Several engineering systems were developed based on these principles. They includes: scanners for laser heat treatment control, hoppers and chutes for transportation of granular media, cutting tools for ultrasonically assisted machining, sensors etc. [Babitsky, 2005]. Below some recently developed systems are described.

3.1 Screening machine

The experimental set-up (Figure 4) was designed to investigate the influence of impacts on the process of separation and transportation in screening machines.

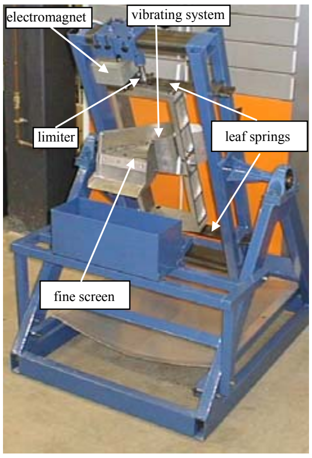

Figure 4. Screening machine.

The main objective when designing was to reach a combination of maximum flexibility and adjustability for experimental purposes on the one hand and simplicity on the other hand. To achieve this goal, a small rectangular screen was chosen with 460x120 mm dimensions corresponding to one segment of the real pretension fine screen.

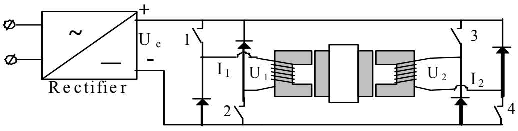

Figure 5. Tandem design of excitation with independent control of each magnet

The vibrating system has mass about 15 kg and is suspended on packs of leaf springs. The natural frequency can be varied in 10-50 Hz range by means of changing the length and number of springs. The leaf springs provide unidirectional reciprocating motion of the screen. The rig allows the direction of vibration to be changed over the whole range from vertical to horizontal. The slope of the screen can be adjusted in both directions (upward and downward) from the horizontal orientation. Two powerful electromagnets are used for excitation, and their armatures are fixed to the vibrating part of the rig. Two adjustable limiters provide the vibro-impact regime of vibration. The half-wave electromagnet is a simple and convenient synchronous transformer of the alternating electrical signal to exciting force in the autoresonant vibrating machine.

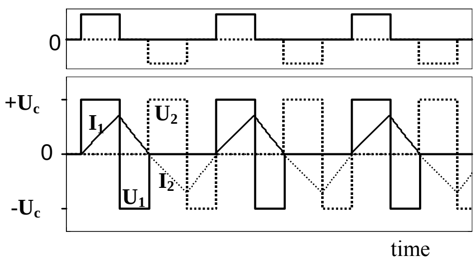

Figure 6. Waveform control (voltages and currents)

The design with two opposite magnets enables the production of alternating force without constant component. The scheme, shown in Figure 5, allows independent control of each magnet.

Both electronic switches in each pair 1,2 and 3,4 are turned on or off simultaneously. The positive voltage +Uc is applied to the coil when both corresponding switches are turned on. Otherwise the opposite voltage -Uc is applied until the current drops to zero.

Under proper control this scheme does not produce either ineffective opposite forces acting simultaneously or constant components of forces. The upper diagram in Figure 6 represents the control time chart: the positive pulses actuate the first pair of switches (1&2) and the negative pulses actuate the other pair (3&4).

The lower chart shows the corresponding waveforms for the magnets' voltages and currents. The I_2 current is shown arbitrary negative to reflect the opposite direction of force it produces. Changing the on-off time ratio (relative pulse duration) of the control signal can change the amplitude of the exiting force (current).

The aim of the autoresonant control system is to transform the vibration sensor signal to proper control. The control must provide the effective work of the electromagnetic exciter and certain phase shift between exiting force and vibration signal.

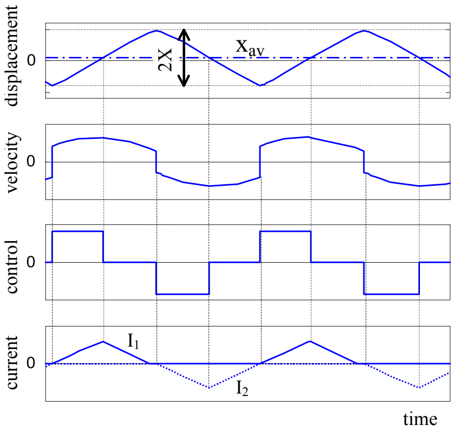

Figure 7. Transformation of the vibration signal to the control signal

These conditions should be met under changing frequency and amplitude of vibration. Unlike conventional resonant machines with frequency control, an autoresonant system does not usually need precise maintenance of the phase shift in the feedback circuit.

One of the possible ways to transform vibration signal by the feedback is shown in Figure 7. It uses both displacement and velocity signals to form the control. The average value x_{av} of the displacement signal is also used (dashed bold line in the upper diagram) as it differs from zero (equilibrium position) for vibration with asymmetric limiters.

3.1 Ultrasonically assisted cutting machine

Figure 8 demonstrates an experimental set-up of ultrasonically assisted cutting machine used in this work. The ultrasonic transducer consists of piezo ceramic rings within a package together with a wave-guide (concentrator).

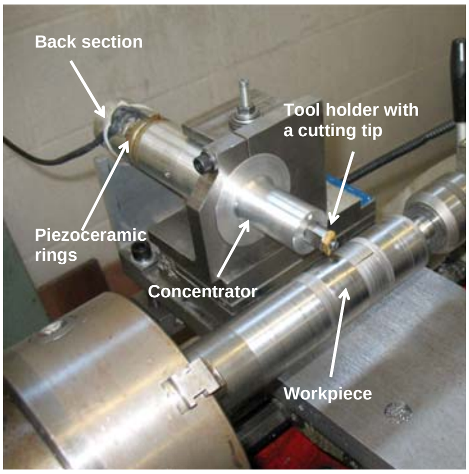

Figure 8. Ultrasonically assisted cutting machine

A cutting tip is fixed in the tool holder installed at the thin end of the concentrator. The transducer is fixed through its developed nodal cross section at the machine tool vertical slide. The workpiece is clamped by a three-jaw spindle chuck and rotates universally by a lathe drive.

When the high frequency electric impulses from an electronic amplifier are fed to the input of the piezo transducer it begins vibrating due to piezo-electric effect. The vibration excites the longitudinal waves in the concentrator, which intensifies the amplitude of vibration in the direction of the thin end and through it vibration of the cutting tip.

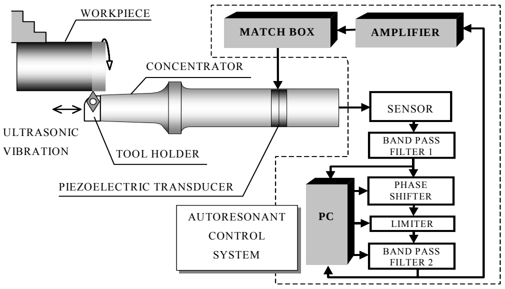

Figure 9. Autoresonant ultrasonic system

It was shown that excitation of the high-frequency resonant vibro-impact mode of the tool-workpiece interaction is the most effective way of ultrasonic influence on the dynamic characteristics of machining [Astashev, Babitsky, 2007; Voronina et al, 2008]. The exploitation of this nonlinear mode needs an analysis of the nonlinear boundary problem for a complex rod structure of the ultrasonic transducer with the variable cross section of its wave guide. The nonlinear boundary condition reflects the process of tool–workpiece interaction during the cutting, which is poorly defined and time varying.

To make the system adaptable to unpredictable variations of cutting conditions, an *autoresonance* control for excitation and stabilisation of ultrasonic vibration was used. In this case (see Figure 9) the amplified signal obtained from the performance sensor is fed to the piezo transducer by means of a positive feedback. This leads to dynamic instability of the mechanical system, which is controlled by intelligent tracing of the optimal relationship between phase shifting and limitation in the feedback circuitry.

4 Conclusions

Autoresonant control is an advantageous alternative to conventional methods of vibration excitation in machines and systems. This allows effective use of nonlinear vibration for intensification of processing. The opportunity of application of the robust and high quality resonant system under wide deviation of processing loads results in essential increase of machine productivity, efficiency and improvement of design.

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