Resonant Excitation of a Composite Beam using Piezoelectric MFC Actuators

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Abstract:
Due to leakage resistances measuring slowly changing loads using piezoelectric sensors is rather difficult while measuring static loads is impossible. Using the functional principle of a scale with a vibrating string a work-around to this problem is found. By evaluating the relation between the load onto the string and the eigenfrequencies of bending vibration of the string the external load onto the string can be determined.
Instead of a string of circular cross-sectional area a thin beam can be used which leads to a preferential vibration direction in direction of least bending resistance. To achieve large signal amplitudes the beam should be excited and vibrating close to its eigenfrequency. To remain in a state of resonance at all times the frequency of excitation must follow frequency alterations due to external influences. Such a frequency locking can be achieved by applying phase-locked loops (PLL) which are widely used within communication technology.
In this contribution an experimental set-up for resonant excitation of a composite beam is presented. A small mass is mounted onto the beam. Its position is adjustable to modify the eigenfrequency of the beam. Using piezoelectric macro-fiber composites for sensing and actuating as well as an integrated PLL circuit the resonant excitation of the beam can easily be achieved even for changing eigenfrequencies.

Keywords: resonance excitation, beam, MFC actuators, phase-locked loops

Introduction

In [1], the adaptronic strut, shown in Fig. 1, for compensating geometric errors in machine tools was presented. To overcome the difficulty of measuring static and slowly changing loads using piezoelectric transducers the functional principle of a scale with a vibrating string was adapted [2]. Within the strut, a thin metal strip is used instead of a string since there is a preferential direction of vibration about the axis of least bending resistance. The metal strip which in the following will be referred to as ‘string’ is excited by a solenoid. The excitation always takes place in resonance. This can be achieved by an appropriate feedback of the frequency information measured with the piezoelectric element as input signal of the voltage controller of the solenoid. The effect is similar to the acoustic feedback of a microphone placed in front of a speaker.

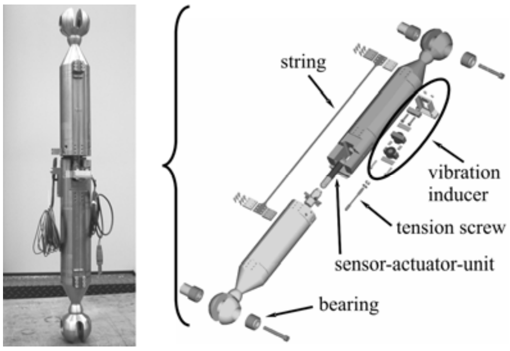

Fig. 1: *Adaptronic strut [1]*

In this contribution, an alternative method for exciting the string is presented. Using phase-locked loops, known for their use in communication technology for the synchronization of two signals by tracking their phases, the resonant excitation of a beam structure can be achieved. For a more detailed investigation an experimental set-up on the basis of a vibrating beam structure is presented.

Phase-locked loops

Phase-locked loops, whose structure is exemplarily shown in Fig. 2, mainly comprise three elements: a voltage controlled oscillator (VCO), a phase detector (PD) and a low pass filter (LPF).

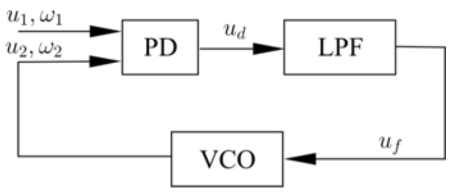

Fig. 2: *Block diagram of a phase-locked loop [3]*

The phase detector compares the two phases of the output signal u_2 of the VCO and the incoming signal u_1. If the two phases are not equal the output signal of PD is non-zero. It consists of two parts, one carrying information about the sum of the two phases, the other carrying information about the difference of the two phases. Taking the center frequency ω_0 of the VCO into account, the phase difference usually is much smaller than the sum of the two phases. Thus, after passing the low-pass filter, the signal u_F only carries information about the phase difference. As input signal of the VCO it modifies the phase φ of u_2 and, due to the relation

$$\omega(t) = \frac{d\varphi(t)}{dt}\,, \tag{1}$$

also the angular frequency ω_2 according to

$$\omega_2(t) = \omega_0 + K_0 u_F(t)\,, \tag{2}$$

with K_0 being the gain of the VCO.

The tracking attitude of the PLL can easily be seen. As long as there is no change in phase of the two signals u_1 and u_2, no phase error occurs and the signals u_d and u_F are zero. When there is a change, the VCO is caused to change the frequency of its output signal such that the phase error vanishes [3].

Experimental set-up

For experimental studies the test-rig shown in Fig. 3 was set-up. It comprises a glass-fibre reinforced composite beam with nine layers of textile glass which is fixed on its left and free on its right end. Two piezoelectric macro-fibre composites (MFC) are glued onto this beam. One of these elements is used as sensor, the other one is used as actuator. The sensor signal is the input of the PLL, which is supplied by a DC source. The output signal of the PLL is amplified (Amp) and builds the input of the actuator. Furthermore, for reasons of processing, it is digitized in the AD and saved in a digital signal processor (DSP). Additionally, a single-point laser vibrometer (LV) with laser head (LH) is used for measuring deflection and speed of the tip of the beam. An additional phase shifter for setting a definite phase relation between actuator input and sensor output was not used.

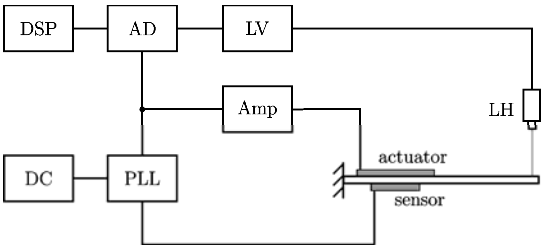

Fig. 3: *Experimental set-up*

At distance x_0 from the tip of the beam, a small box made of paper is mounted onto the beam, as shown in Fig. 4. The box can be filled with sand, either by a continuous mass flow dm/dt or by discrete masses Δm, thus changing the eigenfrequency of the beam. As phase-locked loop an integrated circuit of type CD4046B from Texas Instruments is used. Its integration into the control circuit is shown in Fig. 5. Using capacity C_1 and resistance R_1 the center frequency f_0 of the VCO and, thus, of the PLL is set. Resistance R_2 is used for setting an additional initial frequency offset of the VCO, R_3 is used as a leakage resistance such that the loop filter is not loaded. The loop filter of the PLL is a first order low-pass filter built by the combination of C_2 and R_4. According to [4], its cut-off frequency can be determined to

$$f_g = \frac{\omega_g}{2\pi} = \frac{1}{2\pi R_4 C_2}\,. \tag{3}$$

As phase detector an EXOR-gate is used.

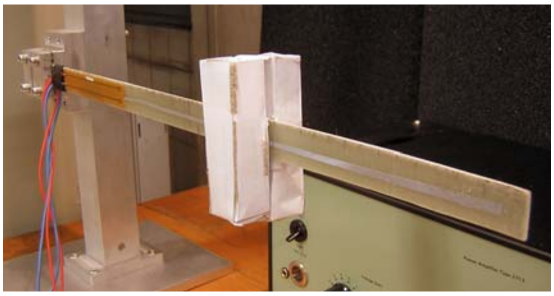

Fig. 4: *Composite beam with paper box mounted*

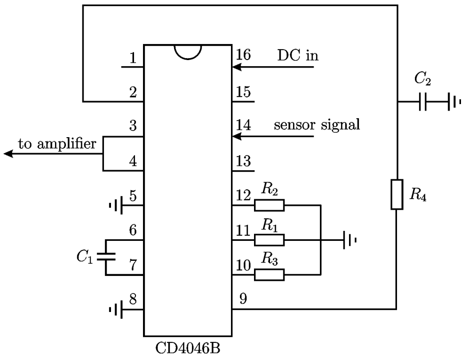

Fig. 5: *Controller with integrated PLL IC*

Characterization of the test-rig

The dimensions of the composite beam are given by cross-sectional area $A = b*h = 2$ mm * 20 mm and free vibration length $l = 430$ mm. The density of the composite material was determined to $\rho = 1760$ kg/m^3. The Young's modulus, however, can solely be approximated to $E = 3.5\mathrm{e}10$ N/m^2, since the composite material is not homogeneous. The eigenfrequencies of the composite beam are measured using a laser scanning vibrometer. The results are shown in Table 1.

Table 1: *Eigenfrequencies of the composite beam*

f_1	7.813 Hz
f_2	43.75 Hz
f_3	121.3 Hz
f_4	242.2 Hz
f_5	400.6 Hz

Consequently, the amplitude of the tip deflection of the beam increases if the excitation frequency is close to one of its eigenfrequencies. This effect is illustrated in Fig. 6, where the course of the tip deflection is shown.

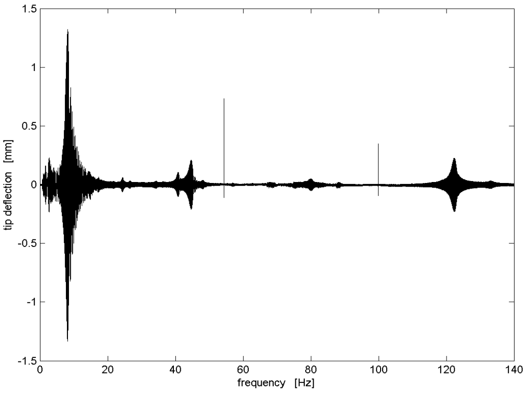

***Fig. 6:** Amplitude of tip deflection for different frequencies*

During all experimental studies presented in this contribution the center frequency of the PLL is set to $f_0 = 7.6$ Hz, i.e. close to the first eigenfrequency of the beam. The cut-off frequency of the low-pass filter is set to f_c = 28.9 Hz. The required electrical components are set according to Table 2.

***Table 2:** Data of electrical components*

R_1	18 kΩ	C_1	2 µF
R_2	820 kΩ		
R_3	22 MΩ		
R_4	5.5 kΩ	C_2	1 µF

Results

In the following, the results of the experimental studies are presented. Firstly, the beam, unaffected of any external influences, is excited by the use of the integrated PLL as a control circuit. The answer of the system is shown in Fig. 7. The amplitude of the tip deflection of the beam rises until it reaches its maximum value. A similar behaviour is achieved if the excitation results from the use of an arbitrary signal generator with amplifier used in a forward control.

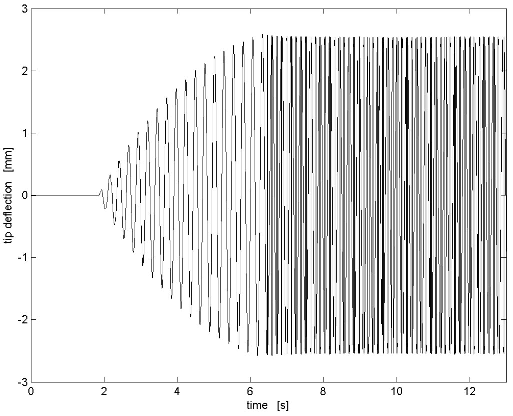

***Fig. 7:** Tip deflection of beam for excitation with PLL without any external influences*

If a constant mass m = 40 g is placed onto the beam at distance x_0 = 180 mm from the tip the eigenfrequency of the beam is changed. With the PLL a resonant excitation is still achievable, as shown in Fig. 8, albeit the maximum amplitude of the tip deflection decreases because of the higher inertia of the beam due to the added mass. By use of the signal generator without adjusting the excitation frequency to the new eigenfrequency, however, the amplitude of the tip deflection decreases even more.

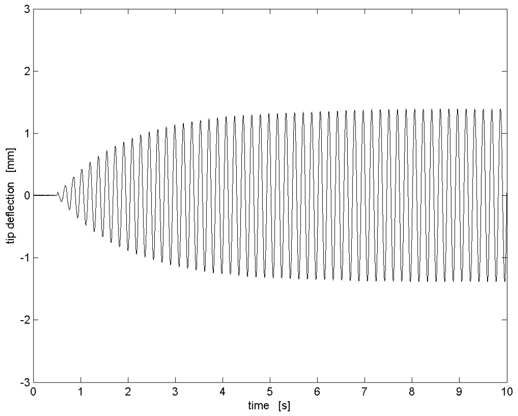

***Fig. 8:** Tip deflection of beam for excitation with PLL with additional mass m = 40 g at x_0 = 180 mm*

A similar behaviour can be seen in the following experiment. A paper box is mounted onto the beam at x_0 = 180 mm from the tip of the beam. After exciting the beam into a resonant oscillation, the paper box is filled with sand by a constant mass flow dm/dt = 3 g/s until the maximum mass $m_{\max}$ = 80 g.

As illustrated in Fig. 9, due to this additional mass, the eigenfrequency of the beam and, thus, the maximum deflection of the tip strongly decrease if the excitation frequency stays constant at f_0 = 7.6 Hz.

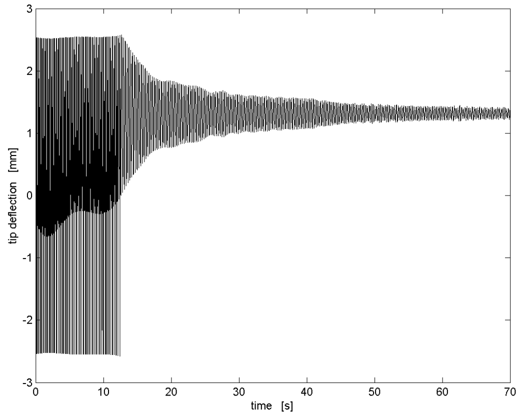

***Fig. 9:** Tip deflection of beam for excitation of constant frequency and mass flow dm/dt = 3 g/s*

Using the phase-locked loop in the feedback path, as illustrated in Fig. 3, the resonant excitation of the beam again can be maintained. The result is depicted in Fig. 10.

When the beam is vibrating in its initial eigenfrequency f_1, again the paper box is filled with sand by a constant mass flow dm/dt = 3 g/s until the maximum mass $m_{\max}$ = 80 g is reached. At first, the amplitude of the tip deflection decreases as a result of the increased inertia of the beam due to the added mass. However, the PLL tracks the frequency course of this oscillation and adjusts the frequency of the excitation to the new eigenfrequency of the system. Thus, the decrease of the amplitude is much less, as can be seen by comparing Figs. 9 and 10.

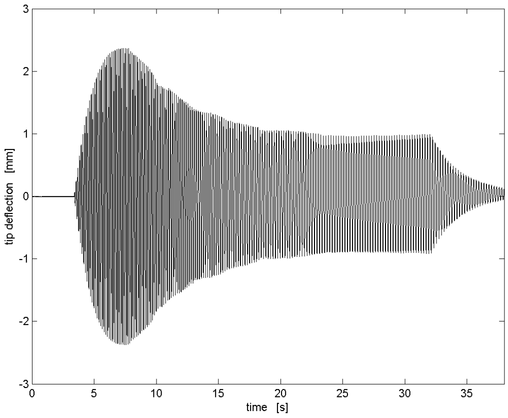

Fig. 10: *Tip deflection of beam for excitation with PLL and for mass flow* dm/dt *= 3 g/s*

Suddenly, at $t \approx 32.5$ s the amplitude of the tip deflection strongly decreases. At this point, the eigenfrequency of the beam leaves the lock range of the phase-locked loop. The PLL no longer tracks the measured signal and the resonant excitation can no longer be maintained.

Fig. 11 depicts the frequency of the PLL output signal depending on mass m and its position x_0 on the beam. The lower limit of the lock range of the phase-locked loop can easily be seen where the frequency tracked by the PLL abruptly breaks down to zero.

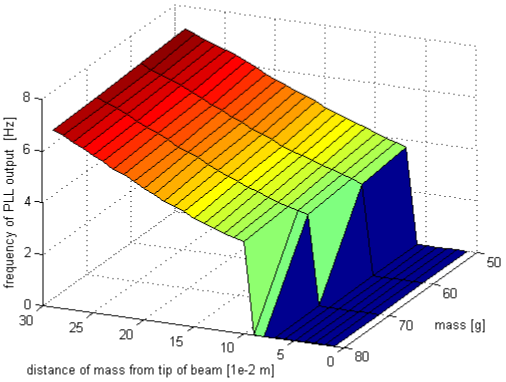

Fig. 11: *Frequency of PLL output depending on mass m mounted onto the beam and its position* x_0 *on the beam*

Conclusion

Phase-locked loops are widely used in communication technology for synchronization by tracking the phases between two signals. By the use of an experimental set-up in this contribution it was shown that this tracking ability can be used for the resonant excitation of a system whose eigenfrequency changes due to external influences. Thus, the use of PLL represents an alternative excitation method to the excitation procedure by using a solenoid with acoustic feedback as shown in [1].

The advantage of the PLL method is the independence on the material of the component of excitation, whereas a solenoid needs material of ferroelectric properties. The disadvantage of the presented excitation procedure lies in the limited frequency range of the PLL. If the phase information gets lost when outside of the lock range of the PLL, which depends on the low-pass filter and the phase detector chosen, the tracking of the PLL stops and the resonant excitation can no longer be maintained. This, however, is solely a problem for operations in the frequency range examined (« 1 kHz) since the lock range of the PLL is rather small in comparison to operations with higher frequencies. The examination and evaluation of the presented concept for higher frequency ranges is object to future studies.

Acknowledgement

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