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SUMMARY

The method of phase-locked loop was adapted for use as a frequency-control system for an ultrasonic transducer. This method provides better control over a greater resonant-frequency deviation than was provided by the previous proportional-control methods. Improved frequency control creates a more constant oscillation amplitude. The phase-locked-loop control of ultrasonic transducers is compared with the self-resonant and the proportional-control systems. Experimental results on a 600-watt magnetostrictive transducer show the frequency-control accuracy to be ±0.5 hertz over a resonant-frequency deviation of 800 hertz from an initial resonant frequency of 25 kilohertz. The amplitude remained constant to within 5 percent of that at resonance.

INTRODUCTION

Ultrasonic systems are composed of magnetostrictive, piezoelectric or electrodynamic transducers, a power amplifier, and a control. Three problems exist in driving high-power ultrasonic transducers: (1) A transducer has to be driving close to its resonant frequency for good efficiency and large amplitude because of its high Q. (2) There are major resonant frequencies other than the one desired. (3) The resonant frequency varies because of temperature changes resulting from self-heating and transducer environment. This variation is great enough to preclude the use of an oscillator and an amplifier in an open-loop configuration. A control system is necessary to maintain the driving frequency at or near transducer resonance in order to obtain constant amplitude of oscillation and maximum efficiency.

Past solutions to this problem have been the use of a self-resonant or a porportional-control system. Both systems control the driving frequency to maintain operation close to the resonant frequency so that a nearly constant amplitude of oscillation can be achieved. The self-resonant system proposed by St. Clair (ref. 1) had a drawback because more than one resonant frequency was present, and it was difficult to get the system to control at the design resonant frequency. The proportional system developed by Potter (ref. 2) was limited in its ability to follow a large frequency variation with sufficient accuracy to maintain the amplitude of oscillation within a given tolerance. This limitation is an inherent steady-state error associated with proportional control.

These past solutions proved acceptable for many ultrasonic-transducer-control problems, but the application of a magnetostrictive transducer at the Lewis Research Center required control over a larger frequency range with a higher degree of amplitude accuracy than that achieved by the proportional system. The transducer was to be used to vibrate a specimen of metal in a liquid-sodium bath so that cavitation damage to the specimen could be studied. Heat conduction from the liquid metal combined with the self-heating of the transducer caused a wide resonant-frequency variation. Thus, a control system that would operate at the design resonant frequency, when this frequency varied over a wide range, was required.

The application of phase-locked-loop control to a magentostrictive ultrasonic transducer is discussed herein, and it is shown why the self-resonant and proportional systems could not meet the control requirements. The operation of the phase-locked-loop control is discussed, and the results of its use in the specific application are given. It should be noted that this method of control is applicable to many other types of frequency-control problems. In particular, other types of ultrasonic transducers such as piezoelectric or electrodynamic can be driven by this type of control system.

SYMBOLS

D difference between initial resonant frequency and resonant frequency at any one time

f_{dr} driving frequency

f_r resonant frequency

K proportional control circuit gain

K_1 slope of phase as function of frequency for small values of deviation from resonance

K_2 maximum rate of change of resonant frequency with time

K' phase-locked-loop-control circuit gain

Q ratio of reactance to resistance of resonant circuit

t	time
$\Delta\varphi$	phase deviation of drive frequency from -90° at resonant frequency

Subscripts:

i	initial
max	maximum
min	minimum

REQUIREMENTS FOR CONTROL

The requirements for an ultrasonic-transducer-control system were determined by the characteristics of the transducer and its application. The specific information required is the design resonant frequency, the amount of control accuracy necessary, and the expected resonant-frequency variation.

The design resonant frequency of the transducer assembly was 25 kilohertz. The position of the nodal supports and the location of the position sensor at an antinode made it imperative that the assembly be operated at only the design resonant frequency.

The transducer characteristics shown in figure 1 give information on control accuracy and method of feedback. Figure 1(a) shows the amplitude of mechanical oscillation for a range of driving frequencies close to the design resonance. The sharpness of the peak requires a frequency control accuracy of ±0. 5 hertz to maintain the amplitude to within 5 percent of its peak value. Increasing temperature during operation causes the resonant frequency to vary from its initial value of 25 to 24. 2 kilohertz after 20 minutes of operation, as shown by the dashed line. The relative phase difference between the mechanical output and the electrical input oscillation of the transducer is shown in figure 1(b). The phase response was used as the automatic control signal because, unlike the amplitude response, it provides a signal unambiguous as to the direction of required correction. A phase difference between 0° and -90° corresponds to a driving frequency below resonance, while a phase difference between -90° and -180° implies operation above resonance. Thus, if the phase is controlled at -90°, resonance will be maintained.

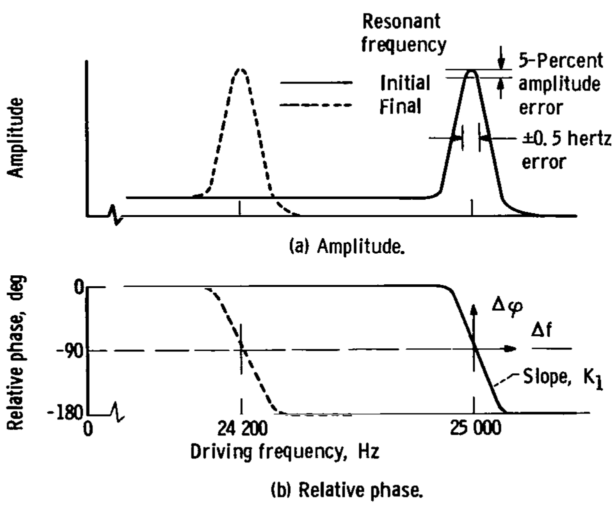

Figure 1. - Characteristics of ultrasonic driver.

The expected resonant-frequency variation was determined by a worst-case test of

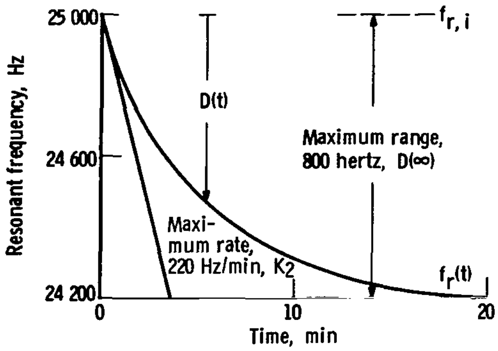

Figure 2. - Resonant-frequency variation (worst case).

the ultrasonic system in this application. The worst case resulted from maximum input electrical power and maximum liquid-sodium temperature. The resonant-frequency variation for time into this sample run is shown in figure 2. A range of 800 hertz and a maximum rate of change of 220 hertz per minute resulted. Typical sample runs were to be from 6 to 20 minutes in duration. Consequently, an automatic control was imperative to obtain the control accuracy.

A summary of control requirements are (1) an ability to control at the design resonance around 25 kilohertz, (2) a control accuracy of ±0.5 hertz from resonance, and (3) a range of 800 hertz with a velocity of up to 220 hertz per minute. It was also desired to have an independent control of power level that would not affect automatic-frequency control.

PREVIOUS CONTROL SYSTEMS

Methods of frequency control previously applied to ultrasonic transducers were investigated, namely, the self-resonant and the proportional systems. The self-resonant system (ref. 1) uses the transducer as the tuning element or tank circuit in an oscillator circuit. Positive feedback is used to sustain oscillation. There are two problems with this system. It will not operate over large independent changes in the power level, and it will operate at any of the resonant modes of the transducer assembly. Use of the self-resonant system was thus abondoned.

The proportional-frequency-control system (ref. 2) is very similar to the phase-locked-loop control that has been used for years on a similar problem in the field of telemetry (refs. 3 and 4). Since both these methods meet the requirements of operation over large independent changes in power level and operation at only the design resonant frequency by forcing operation at this point, both these systems are discussed and contrasted.

PROPORTIONAL- AND PHASE-LOCKED-LOOP OPERATION

The block diagram of the proportional- and phase-locked-loop-control systems is shown in figure 3. The transducer is driven by a power amplifier that, in turn, is driven by a voltage-controlled oscillator. The power amplifier has a gain control that permits an

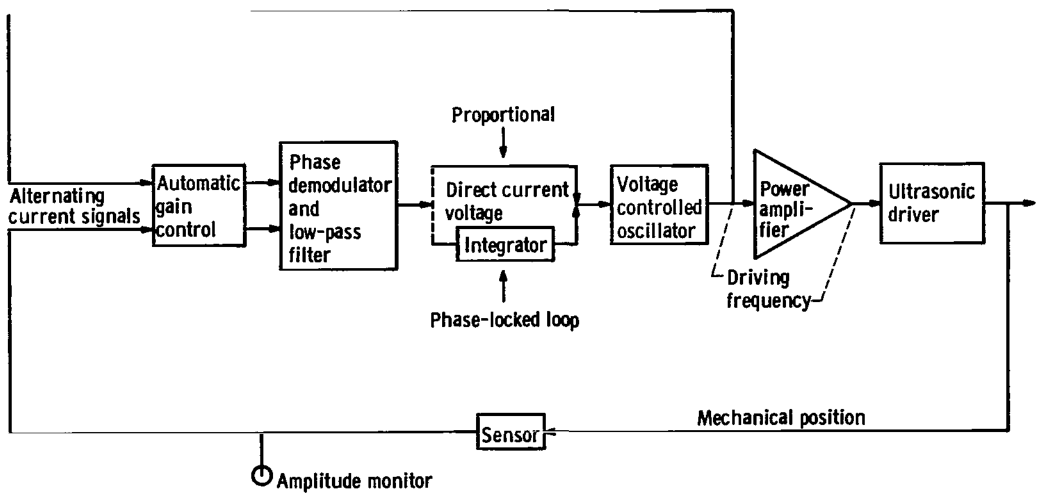

Figure 3. - Block diagram of proportional and phase-locked-loop control systems.

independent adjustment of power level. The change in output frequency of the voltage controlled oscillator from its initial value is proportional to the applied direct-current voltage at the input. In the case of the proportional-control system, the voltage controlled oscillator input is obtained from the low-pass filtered output of a phase demodulator. The input to the phase demodulator is two electrical signals. The position feedback signal represents the mechanical oscillation, while the reference signal is the electrical input driving frequency. It is the relative phase of these two signals that must be controlled to -90° to maintain resonance. The filtered output of the phase demodulator is a direct-current voltage proportional to the deviation of the phase difference between the signals from the -90° point. This voltage is proportional to the error between the driving frequency and the resonant frequency and is applied to the voltage controlled oscillator to bring the driving frequency toward resonance.

The proportional-control error can be calculated from two equations and a term defining the range. The proportional-control system equation is

$$f_{dr} = f_{ri} - K \tag{1}$$

The transducer characteristic equation from figure 1 is

$$\Delta\varphi = K_1(f_{dr} - f_r) \tag{2}$$

The definition that gives the range in terms of the resonant frequency is

$$D(t) = f_r(t) - f_{ri} \tag{3}$$

The solution of the three equations gives the closed-loop error,

$$f_{dr} - f_r = \frac{-D}{1 + K_1 K} \tag{4}$$

The error increased in proportion to range, but inversely in proportion to open-loop gain, K.

The phase-locked-loop control has an integrator inserted between the low-pass filter and the voltage controlled oscillator, as shown in figure 3. This integrator makes it possible to have a voltage on the input to the voltage controlled oscillator without any error.

The phase-locked-loop error can be calculated from equations (2) and (3) as well as the control equation

$$f_{dr} = f_{ri} - K' \int \Delta\varphi \, dt \tag{5}$$

If a range input of

$$D(t) = K_2 t \tag{6}$$

is used, the error will be

$$f_{dr} - f_r = \frac{K_2}{K' K_1}\left(1 - e^{-K' K_1 t}\right) \tag{7}$$

Since the frequency error must be less than ±0.5 hertz, the open-loop control gain K' must be

$$|K'| \geq \frac{|K_2|_{max}}{0.5|K_1|} \tag{8}$$

It is noticed in equation (7) that the phase-locked-loop-control error is not a function of resonant-frequency range of variation but only of the rate of variation. In this application where K_2 was relatively small and D was large, the phase-locked-loop method of control was advantageous.

Since the phase-locked-loop-control error was less than that which would be expected from a redesign of the available proportional controls, it was constructed. Implementation of the system was accomplished easily with commercially available equipment. In this application the automatic-gain controls were Schmidt triggers that converted the input sine waves into signals of constant amplitude. The phase demodulator was of the ratio-detector type.

RESULTS

The phase-locked-loop control was applied to the 600-watt magnetostrictive ultrasonic transducer used in the liquid-sodium cavitation experiment. Environmental and operating conditions similar to the worst-case assumptions used to specify system requirements were established, and the system was put into automatic control. Several 20-minute test runs were made during which the resonant-frequency drift was recorded from a frequency counter and the control accuracy was monitored by the peak-to-peak amplitude. The results of several test runs were constant amplitude within 5 percent of peak amplitude and control over resonant-frequency variations up to 810 hertz from the starting resonant frequency of 25 kilohertz. Operation took place only at the 25-kilohertz design resonant frequency.

The test results confirmed the ability of the phase-locked-loop system for operation over a wide range of frequency variation with accuracies of control that were as good as or better than the proportional system. An accuracy of ±0.5 hertz was inferred from the 5-percent amplitude variation for resonant-frequency changes of more than 800 hertz from 25 kilohertz. This is a frequency variation of more than 3 percent from the initial resonant frequency. This range of 800 hertz, or 3 percent, from 25 kilohertz is not limited by theory as a maximum for this control but is given herein as an indication of the extent to which the control system was tested.

CONCLUDING REMARKS

The method of phase-locked-loop frequency control of ultrasonic transducers offered the advantages of increased accuracy and range of frequency control over the proportional system that resulted in the reduction of amplitude variations during operation. Phase-locked-loop control also maintained control at the design resonant frequency of the transducer assembly to offer better performance than the self-resonant-control system.

A test of the phase-locked-loop system on a 600-watt magnetostrictive transducer provided constant operation at frequencies within ±0.5 hertz of resonance as implied by monitoring output signal amplitude for a resonant-frequency variation of 810 hertz from the initial resonance of 25 kilohertz. Phase-locked-loop control is applicable to frequency-control problems of many types and is not limited to the specific application discussed in this report.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 19, 1966,
129-03-03-03-22.

REFERENCES

1. St. Clair, Hillary W.: An Electromagnetic Sound Generator for Producing Intense High Frequency Sound. Rev. Sci. Instr., vol. 12, no. 7, May 1941, pp. 250-256.
2. Potter, E. V.: An Automatic Frequency-Controlled Oscillator and Amplifier for Driving Mechanical Vibrators. Rev. Sci. Instr., vol. 14, no. 7, July 1943, pp. 207-215.
3. Nielson, Carl L.: Principles and Applications of Phase-Lock Detection in Phase-Coherent Systems. Rep. No. HTR 57-003, Hallamore Electronics Co., Anaheim, Calif., Apr. 1957.
4. Weaver, C. S.: Thresholds and Tracking Ranges in Phase-Locked Loops. IRE Trans. on Space Electronics and Telemetry, vol. SET-7, no. 3, Sept. 1961, pp. 60-70.

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