



# Automatic vibration mode selection and excitation; combining modal filtering with autoresonance



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## ABSTRACT

Autoresonance is a well-known nonlinear feedback method used for automatically exciting a system at its natural frequency. Though highly effective in exciting single degree of freedom systems, in its simplest form it lacks a mechanism for choosing the mode of excitation when more than one is present. In this case a single mode will be automatically excited, but this mode cannot be chosen or changed. In this paper a new method for automatically exciting a general second-order system at any desired natural frequency using Autoresonance is proposed. The article begins by deriving a concise expression for the frequency of the limit cycle induced by an Autoresonance feedback loop enclosed on the system. The expression is based on modal decomposition, and provides valuable insight into the behavior of a system controlled in this way. With this expression, a method for selecting and exciting a desired mode naturally follows by combining Autoresonance with Modal Filtering. By taking various linear combinations of the sensor signals, by orthogonality one can “filter out” all the unwanted modes effectively. The desired mode’s natural frequency is then automatically reflected in the limit cycle. In experiment the technique has proven extremely robust, even if the amplitude of the desired mode is significantly smaller than the others and the modal filters are greatly inaccurate.

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## 1. Introduction

Sensors, actuators and mechanical structures are often designed to operate at resonance and with a specific vibration pattern. One example of this is a high-Q ultrasonic transducer which must operate at resonance to achieve peak amplitude. In Near-field Acoustic Levitation, various structural modes may be excited simultaneously to induce levitation and torque on an object [1]. To maintain resonance, a feedback loop and a resonance frequency tracking algorithm is typically required, as the natural frequency drifts when ambient conditions or loading change. Three of the most widely used feedback (or pseudo-feedback) methods for resonance tracking are: Phase Locked Loop (PLL) [2], Hill Climbing (optimum seeking) [3], and Periodic Frequency Sweep [4]. But these three methods, though useful in many applications, have significant drawbacks. For example, the PLL attempts to lock onto a predetermined phase shift, but requires PID tuning and can be slow to lock. Hill climbing must continually test the frequencies within a vicinity, and performance may be insufficient. In cases where resonance must be achieved at all times, a Periodic Frequency Sweep is useless. But another method for maintaining resonance does exist, and has been known for a long time. The method is commonly referred to as Autoresonance (AR), but may also be referred to as Self-Excitation [5]. It locks onto resonance quickly, implementation is relatively simple, and it could excel in applications where the other three methods fail. This method however has a major drawback of its own. Indeed, the

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literature mainly discusses single input and output systems [6,7]. For multiple degree of freedom systems, the excitation of a particular mode can be difficult [8].

Because so many physical systems possess multiple modes, AR has suffered limited popularity as an algorithm for exciting resonance, with a few exceptions. It has been quite successful in tuning of PID controllers [9,10], commonly known as Autotuning. With this approach it is used to identify some of a system's parameters by placing a relay in a negative feedback loop. But these methods do not address full systems with many flexible modes, nor do they develop a method for choosing which mode(s) will take part in an oscillating limit cycle. In another successful application, AR has been made to reliably excite a specific mode with the addition of a bandpass filter [6]. This approach is particularly useful in the excitation of Quartz Tuning Forks [11]. But even though this method has the advantage of using only a single sensor, it is somewhat crude, as it is dependent on the filter order and requires one to know the vicinity of the resonant frequencies.

The present paper attempts to modify AR such that one can efficiently excite but also select a particular vibration mode. One source of difficulty in selecting a particular mode when multiple modes are present is that predicting the frequency of the limit cycle, regardless of the selection method, may be a complex undertaking. Therefore, the approach of this paper is to first derive a single, concise expression to predict this frequency. This expression is based on modal decomposition and a novel method for inducing a limit cycle at any of the system's natural frequencies follows. This method combines AR with Modal Filtering (MF).

MF was first proposed by Meirovitch and Baruh in 1982 [12], and exploits the bi-orthogonality between the vibration modes of a system. MF works by taking a linear combination of multiple sensor signals such that all modal responses but one are canceled out. This lends itself to AR, as shown in the paper, and the excitation mode can now be chosen. To excite a desired mode precisely, it will be demonstrated that the user needs only to make a rough estimate of the corresponding mode shape, as perfect cancellation is not required for successful mode selection. This eliminates a major weakness of AR, opens up the possibility for more effective resonance tracking and provides a natural way for producing specific vibration patterns in a structure. It should be noted that at no time is the natural frequency of the desired mode predetermined by the user, and the algorithm locks onto this frequency automatically.

In this paper, the AR phenomenon will be discussed in the context of a general second order linear system. First, a mathematical model will be developed which attempts to predict the frequency and amplitude of the limit cycle. Next, AR will be combined with MF (MFAR) to excite a desired mode using multiple sensors. Following this, the effectiveness of MFAR is explored when the eigenvectors of the system are not precisely known. And finally, data from MFAR applied in simulation and on a real multi-degree of freedom system are presented and analyzed. Here, the power of the combined approach consisting of MFAR is clearly demonstrated.

## 2. Modal decomposition, unity feedback and the limit cycle

This section derives the frequency and amplitude of the limit cycle of a general second order system excited by AR. This will be the foundation for the following sections, where a new method for selecting and exciting a particular mode using AR without a bandpass filter is developed.

Consider the general second order system with  $N$  degrees of freedom.

$$\begin{aligned} M\ddot{q} + D\dot{q} + Kq &= Bu, \quad q \in \mathbb{R}^N, \quad u \in \mathbb{R}^m \\ y &= C_q q + C_{\dot{q}} \dot{q} \end{aligned} \quad (1)$$

Here  $M, D, K$  are the mass, damping and stiffness matrices,  $u$  is the input vector,  $B$  is the input shaping matrix and  $y$  is the measured output, which is a linear combination of the states  $q$  and its time derivative  $\dot{q}$ .

Assume  $D$  is proportional [13], the normal modes  $\phi_p$  of the undamped system are computed as

$$\omega_p^2 M \phi_p = K \phi_p, \quad p = 1, 2, \dots, N \quad (2)$$

and can be used to diagonalize  $M, C, K$ . Here,  $\omega_p$  is the natural frequency of the  $p$ th mode. Thus we get,

$$\Phi^T M \Phi = I, \quad \Gamma = \Phi^T D \Phi, \quad \Phi^T K \Phi = \Omega, \quad \Phi = [\phi_1 \quad \dots \quad \phi_N] \in \mathbb{R}^{N \times N} \quad (3)$$

and  $\Omega = \text{diag}\{\omega_p^2\}$ ,  $\Gamma = \text{diag}\{2\zeta_p \omega_p\}$ ,  $p = 1, 2, \dots, N$ , where  $\zeta_p$  is the modal damping ratio.

If we choose a single mode and a single actuator, by exploiting bi-orthogonality

$$y = \phi_p^T M q = \eta_p, \quad B = b \in \mathbb{R}^N, \quad (4)$$

where  $\eta_p$  is the  $p$ th modal coordinate. Employing the transformation:

$$q = \Phi \eta. \quad (5)$$

Assume proportional damping [14] and  $u$  is a scalar input. Substituting into (1), the result is a decoupled system of equations in modal coordinates.

$$I\ddot{\eta} + \Gamma\dot{\eta} + \Omega\eta = \Phi^T b u, \quad \eta \in \mathbb{R}^N \quad (6)$$

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