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Dual frequency parametric excitation of a nonlinear, multi degree of freedom mechanical amplifier with electronically modified topology

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ABSTRACT

Mechanical or electromechanical amplifiers can exploit the high-Q and low noise features of mechanical resonance, in particular when parametric excitation is employed. Multi-frequency parametric excitation introduces tunability and is able to project weak input signals on a selected resonance. The present paper addresses multi degree of freedom mechanical amplifiers or resonators whose analysis and features require treatment of the spatial as well as temporal behavior. In some cases, virtual electronic coupling can alter the given topology of the resonator to better amplify specific inputs. An analytical development is followed by a numerical and experimental sensitivity and performance verifications, illustrating the advantages and disadvantages of such topologies.

1. Introduction

Amplifiers enhance weak physical signals and increase their observability in various fields of engineering [1–4]. Their physical principle by which amplification is achieved differs in accordance with their utilization and role [5], and low loss mechanical amplifiers can perform better than their electronic counterparts [6]. Therefore, the present work focuses on mechanical amplifiers with multiple inputs and outputs, which can handle multiple signals simultaneously. These can be used for multiple antenna transmitters [7] and multiple input multiple output communications [8]. When different inputs act on the multi degree of freedom (MDOF) amplifier at different locations, the response is projected differently on its normal modes [9], allowing for their detection and amplification. Moreover, the MDOF amplifier normal modes can be designed to increase the amplifier gain and sensitivity with respect to specific inputs according to their frequency and point of action.

It has been shown that it is advantageous to utilize parametric excitation to achieve large amplification [10,11]. Additionally, certain parametric excitations, e.g., degenerate amplifiers [12], have a fixed and narrow bandwidth, which allows only amplifying specific frequencies. This property may hinder the ability to amplify a general input signal. For the degenerate amplifier, a signal with a frequency different from twice the natural frequency is not amplified. To overcome this problem, several methods are devised and used.

In previous work [13] the dual frequency parametric amplifier (DFPA) scheme was introduced. The scheme utilizes the advantages of two operating modes of parametric amplifiers, a degenerate, and a non-degenerate mode. According to the

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DFPA scheme, the amplifier is parametrically excited (pumped) simultaneously at two algebraically related frequencies ω_a and ω_b. The degenerate mode is realized by pumping the amplifier at a frequency close to twice the natural frequency (ω_n), $\omega_a \approx 2\omega_n$, while the non-degenerate mode is realized by pumping it at $\omega_b \approx \omega_n - \omega_r$, where ω_r is the input signal frequency. While the degenerate mode produces large amplification, it lacks the ability to practically amplify signals with frequencies different from twice one of the amplifier's natural frequencies. The non-degenerate mode, on the other hand, is utilized to amplify single harmonic signals out of a possible wide-band, while producing relatively small amplification. The DFPA benefits from both operating modes, therefore allows to considerably amplify single harmonic signals out of a possibly wide-band, while retaining sensitivity to the input amplitude and phase. This amplifier can be used to detect the effect of unbalance in rotating structures without spinning them at critical speeds [14,15].

Another method to extend the narrow bandwidth limitation of a typical single degree of freedom degenerated amplifier, is to revise its topology by increasing the number of degree of freedom. By doing so, the amplifier now has several natural frequencies, therefore several single harmonic inputs can be amplified. However, its topology should be carefully designed to avoid undesired effects such as primary and internal resonances [11,16]. Additionally, care should be taken as to where on the structure the inputs or forces [5] act, and what is measured. To allow more flexibility, electronic, real-time topology modification can be implemented in the amplifier by employing sensors, actuators and a fast-digital signal processor. The incorporation of actuators in a closed-loop allows to modify the stiffness and in fact the topology, leading to some control over the natural frequencies and normal modes. Natural frequency modification is beneficial, because it allows to widen the frequency band of input signals that can be amplified. For example, when operating in the degenerate mode, a certain change in the natural frequency doubles the frequency of the input signal that can be amplified.

Normal modes modification is shown herein to be essential in some cases because it allows to increase sensitivity and observability of certain input patterns. Consider the case of a symmetric system with three DOF, as shown in Fig. 1, where the input force acts between m_1 and m_3, and the sensing is done by measuring the relative displacement between m_1 and m_2. If the input resonates the system at the third natural frequency, hence the third mode, the input cannot be observed. Therefore, by tuning the stiffness, the second and third modes are exchanged, and the signal can be observed and amplified.

When principal parametric resonance is employed in a linear system, it may lose its dynamic stability, and unbound large amplitudes are produced. The Ince-Strut diagram [17] depicts the stability regions of an undamped single degree of freedom system subjected to various parametric excitations. In practice, either the large amplitudes result in a catastrophic failure [18], or they are limited by nonlinearities, such as nonlinear cubic stiffness. If large, but bounded amplitudes are produced, a limiting nonlinear cubic stiffness may be due to the extension of the neutral axis [19–21]. In order to describe the dynamical behavior of physical systems, weak nonlinear stiffness is considered in the model.

Previous publications [13,14,22] have addressed single degree of freedom systems with weak cubic nonlinear term, or a method affecting a single mode [14,15] of a weakly nonlinear system. The present paper expands this idea into MDOF vibrating systems, where all the natural frequencies and normal modes are considered. It has been observed, as reported here, that this expansion requires attention to additional details as some difficulties arise. To avoid some of the difficulties such as internal resonances, an optimization procedure was integrated during the mechanical design. A novel approach to circumvent problems such as observability and sensitivity were dealt by incorporating real-time topology modification.

The degenerated operating mode of a lightly damped parametric amplifier is narrow banded in comparison to a primary resonance, which is already narrow banded. Therefore, parametric amplifiers can be very sensitive to small modeling errors that influence the estimated natural frequencies. It is demonstrated in the paper that a model updating stage [23], based on measured data improves the accuracy and hence the performance greatly. The model updating approach uses multi-input model identification, a linear model update stage followed by a nonlinear optimization stage.

The paper begins with introduction of the experimental system and description of the problem. Afterwards, the governing equations of motion are developed and solved for the multiple input, multiple output case. The third part deals with numerical validation and experimental verification. Lastly, conclusions and possible implementations are discussed.

2. The experimental rig and setup

In what follows, a nonlinear multi degree of freedom system, whose model is shown in Fig. 2, is studied. The model is characterized by particle masses $m_\bullet$, linear dashpots $c_\bullet$, linear stiffness $k_\bullet$, time varying stiffness $k_m(t)$, and nonlinear cubic

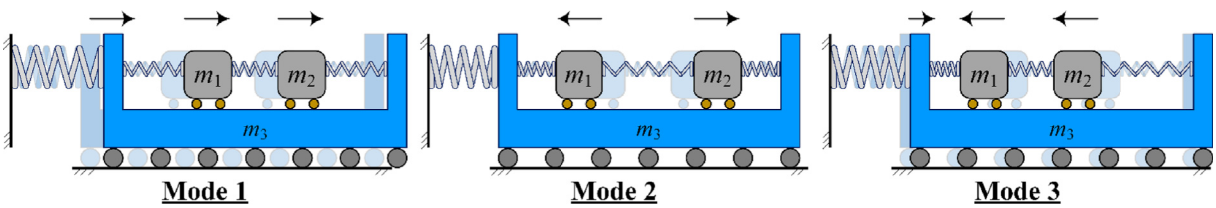

Fig. 1. The experimental system mode shapes.