AMB Vibration Rejection Study: Adaptive Algorithms, Notch Filter and Notch Exciter

Iñigo Arredondo[1,a], Josu Jugo[1,b]
[1]Barrio Sarriena s/n, Dpto. Electricidad y Electrónica. Fac. Ciencia y Tecnología. UPV/EHU
48940 Leioa (Bizkaia), Spain.
[a]iarredondo@essbilbao.com, inigo.arredondo@ehu.es, [b]josu.jugo@ehu.es

Abstract: The vibration rejection is one of the main characteristics to study in the AMB based machine's field, mainly due to the possibility of active control. In this paper four options are studied, on one hand, the well-known solutions utilizing adaptive algorithms and Notch filter, and on the other, the combination of these both (leaving the vibration in open loop) and a new method with a Notch Exciter. As the result of the comparison between them it is concluded that the election of one of the methods depends on the used specific system. Even though, the new proposed solution based on the Notch Exciter seems to be a good alternative for a lot of purposes due to its easy implementation, high working frequency range, low computational cost and high robustness.

Keywords: AMB, Notch Filter, Notch Exciter, Vibration Rejection

Introduction

In the machining field, the mechanical accuracy can be limited by the vibrations and an active control can be considered to achieve better results. Particularly, several applications depend considerably on the positioning of the end of the spindle, but its dynamics is perturbed by the forces generated inherently due to the rotation and the inevitable unbalance of the rotor.

Although there are mass balancing techniques, better results can be obtained combining them with an active control. The implementation of this active controlling into the systems can be performed in several ways, such as the inclusion of dumpers in a ball bearings based machine. Nowadays, the use of Active Magnetic Bearings (AMBs) may be a good choice, knowing their main advantages (no lubrication, no cooling, larger life,...). Using this technology for maintaining the rotor in levitation, it is possible to place accurately the spindle and to counter undesirable effects by controlling properly the bearings' generated forces.

To accomplish this objective several options can be applied such as robust (QFT, LQR, H_∞)[1] or adaptive control techniques [2] and the utilization of a Notch filter [3]. In this work other solution, the Notch exciter, is studied and compared with the previous options.

This paper is organized as follows: Firstly a problem statement and a sum up of the vibration reduction methods compared in this study are presented. Then the pros and cons of each one are discussed and some experimental results are shown. Finally, the conclusions and future work.

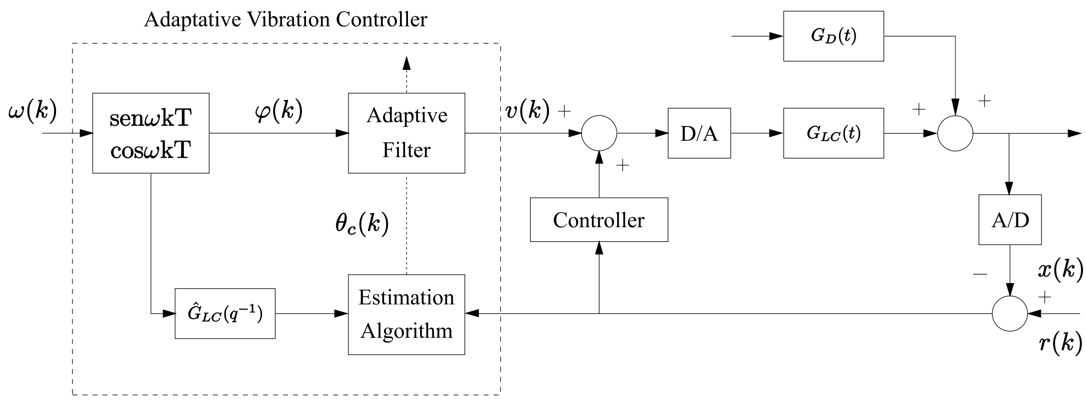

Figure 1: AFVC scheme

Vibration reduction methods

One of the most important characteristics of the systems with rotary elements, as the AMBs based ones, is the unbalance present in the spindle. Its influence could be more or less noticeable depending on several factors. On one hand, the deviation magnitude between the mass center and the principal axis of inertia (e_i with $i = x, y$ depending on the axis) and on the other hand, the cross elements of the inertia matrix (I_{kl} with $k, l = x, y, z$ depending on the term). The main consequence of this unbalance is the appearance of a centrifugal force synchronous with the rotation speed (Ω),

$$\begin{bmatrix} F_{ctfx_{xi}} \\ \tau_{ctf\theta_{xi}} \\ F_{ctfy_{yi}} \\ \tau_{ctf\theta_{yi}} \end{bmatrix} = \omega^2 \begin{bmatrix} -me_{yi} & me_{xi} \\ I_{yzi} & I_{xzi} \\ me_{xi} & me_{yi} \\ -I_{xzi} & -I_{yzi} \end{bmatrix} \begin{bmatrix} sin\omega t \\ cos\omega t \end{bmatrix}, \quad (1)$$

where F_{ctf} represents a centrifugal force and τ_{ctf} a torque.

As can be appreciable in the Eq. 1, if a high rotation speed performance is desired, the vibration could be large. Therefore, if a precise positioning is required, countering this perturbation is desirable.

To counter this vibration four algorithms are compared: Adaptive Feedforward Vibration Control (AFVC), Notch Filter, AFVC with Notch Filter and Notch Exciter.

Adaptive Feedforward Vibration Control

Adaptive algorithms result a good solution widely mentioned in the literature [2, 4]. The technique is based on the generation of one sinusoid which acts in counterphase with the provoked by the unbalance (Eq. 1).

$$v_{x1}(t) = A_{x1} sin(\omega t) + \varphi_{x1} = A_{1x1} sin(\omega t) + A_{2x1} cos(\omega t) \quad (2)$$

To adapt the A_{1x1} and A_{2x1} parameters many algorithms can be utilize, in this case, the choice is a recursive minimum square with covariance reset and weighting, algorithm [5]:

$$\theta_c(k) = \theta_c(k-1) + \frac{P\,\varphi(k)^T x(k)}{1 + \gamma\, tr\ (\varphi(k) P \varphi(k)^T)}. \tag{3}$$

In this equation k represents the sampling instant, θ_c the adaptive parameters ($A_{1x1}$and A_{2x1} for each axis and bearing), P the covariance matrix, φ the known parameters, tr the trace of the matrix, γ a weight and x the position of the spindle.

The purposed scheme for this paper is shown in Fig. 1. Here G_D is the perturbation transfer function, G_{LC} the plant of the system, A/D and D/A the digital-analog converters and r the reference. The $\hat{G}_{LC}$ transfer function is an estimation of G_{LC} in the stationary state to perform a "filtered-x" [6] configuration. This type of adaptive scheme is used to avoid the disturbances at the output of the plant. The other parameters are the ones detailed in Eq 3.

Notch Filter

The principle of this vibration countering is to add a Notch Filter (Eq. 4) tuned at the rotation frequency before the controller.

$$N(\omega) = \frac{s^2 + 2\zeta_1 \omega s + \omega^2}{s^2 + 2\zeta_2 \omega s + \omega^2}, \tag{4}$$

where ω is the rotation velocity and ζ_1 and ζ_2 determine the quality factor (Q) of the filter.

The result is to keep the perturbation in Open Loop (OL). Since the resonances of the OL are displaced when closing the loop, depending on the system and controller, the result may be better with the Notch Filter than without it.

Adaptive Feedforward Vibration Control with Notch Filter

In this case, the combination of the AFVC and Notch filter is established. In this way, the control loop is better decoupled because the stability control (PID) is in charge only of the stabilization and the AFVC is dedicated to reduce the vibration. The purposed scheme is depicted in Fig. 2, where the dynamics decoupler is the Notch Filter.

Notch Exciter

Unlike in the Notch Filter case, the base of this vibration reduction choice is to excite the perturbation demanding greater effort to the controller. The achieved effect is an integral action at the rotation frequency. It is important to note that the typical influence of integral dynamics in the stability of the system should be taken into account when this method is implemented.

The Notch Exciter has the same structure as the Notch filter but interchanging ζ_1 and ζ_2. It is also placed before the controller in the loop.

The main advantage of this method is that it can reduce the perturbation in all of the working range if stability is guaranteed.

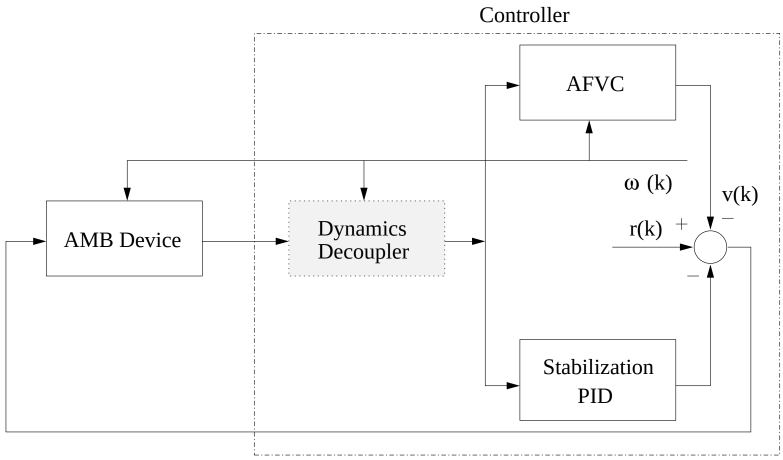

Figure 2: AFVC with Notch Filter scheme

Results

All of these control options are tested in simulation and experimentation, in an AMB based testbed. This workbench is based on the *MBC500 Rotor Dynamics* of LaunchPoint technologies, which is a laboratory device specially designed for research purposes. It is composed of two AMBs and a rotor which includes an air turbine drive, allowing speeds up to 22000*rpm*. The Digital Signal Processor (DSP) *DS1003* of dSPACE is used to close the loop with real-time characteristics.

The study compare the amount of achieved reduction, the frequency range of application, the robustness (external perturbations and noise) and the computational cost.

Adaptive Feedforward Vibration Control

With this option the main advantage is that it can be achieved a high vibration reduction that is dependent on the stable operating frequency range. On the other hand, the algorithm needs a good measure of the rotating frequency, because it is not adapted (see Eq 2) and a precise generation of the sinusoidal signal. Moreover, non-linear behavior could imply a non sinusoidal position output and hence, less effectiveness of the control. The computational cost is high and, even more, if the frequency measure has to be corrected via an Frequency Locked Loop (FLL) device or a Kalman Filter (KF) [7].

Notch Filter

As has been mentioned before, the main drawback of this method is that it is not effective in the whole frequency operating range. However, it is robust and the computational cost is low. Even if the rotating frequency is not measured very accurately the decoupling can be adjusted changing the narrowness of the filter. Moreover, the low computational cost allows to include any method of frequency estimation.

	Vibration Reduction	Frequency Range	Robustness	Computational Cost
AFVC	High	Depending on Stable Operating Range	Low	High
Notch Filter	Medium	Depending on OL/CL frequency response	High	Very Low
AFVC + NF	High	Shorter than AFVC case	Low	High
Notch Exciter	Medium	Depending on Stable Operating Range	High	Very Low

Table 1: Vibration reduction methods comparison

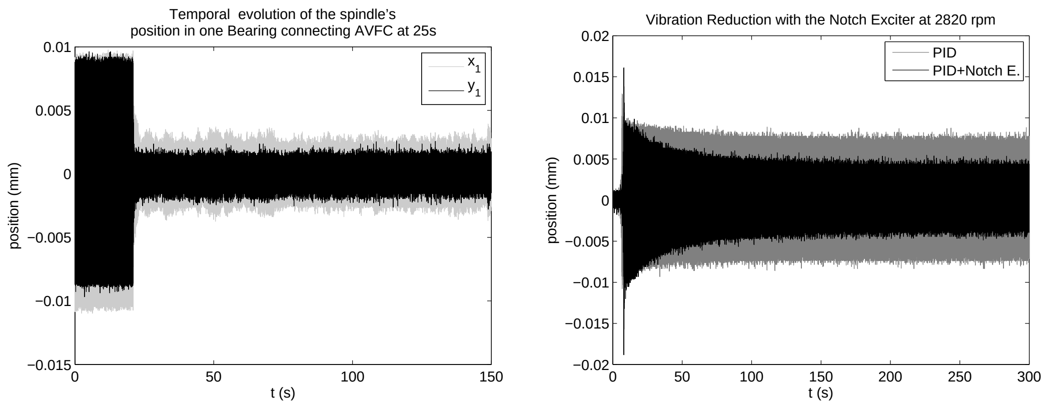

Figure 3: Experimental results utilizing AFVC and Notch Exciter at 2820 rpm

AFVC with Notch Filter

The combination of the AFVC and Notch Filter achieves a vibration reduction in the frequency operating range continuously. Unlike the notch filter whose perturbation minimization depends on the frequency response of the system, this method ensures a continuous vibration reduction. However this solution has the disadvantages of the AFVC algorithm in robustness and computational cost.

Notch Exciter

As the Notch Filter, the Notch exciter has the advantages of robustness and computational cost, but since the working principle is totally different, the operating frequency range is continuous. This feature overcome the main drawback of the Notch Filter method and make possible to achieve vibration reduction in a large variety of systems. The amount of reduction depends on the Notch Exciter design, but, if it is not included any adaptation, it is dependent on the frequency response of the system. It is important to note that, in any case (in the operating range), there will be a reduction.

Table 1 summarizes the features of each control scheme and in Fig. 3, some experimental results utilizing AFVC and Notch Exciter are shown.

Conclusions and future work

The AMB technology is very suitable for counteracting the vibrations generated when the systems have rotary elements. Since this perturbations are not avoidable with the standard compensating methods and became larger with the rotation speed, several active control schemes are proposed and compared.

Concretely four options are studied: AFVC, Notch Filter, AFVC with Notch Filter and Notch Exciter. Each one has pros and cons and its utilization depends on the specific application. For example if high vibration reduction is needed in a clean environment AFVC could be a good alternative, if the work operating frequency is fixed the Notch Filter might be the choice. However the most versatile, low cost and robust option seems to be the Notch Exciter.

As future work, it is proposed to enhance the Notch Exciter with a light adaptive algorithm or a KF to achieve better vibration results. In this case, the parameters to adapt will be ζ_1 and ζ_2. The application of this technique will be only worthy when a large vibration reduction is required.

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