Frequency error rejection for vibration minimization in an AMB system

I.Arredondo
D. Electricity and Electronics, F. Science and Technology, Campus Leioa (UPV/EHU), P.B. 48940 , Bizkaia, Spain
inigo.arredondo@ehu.es
J. Jugo
D. Electricity and Electronics, F. Science and Technology, Campus Leioa (UPV/EHU), P.B. 48940 , Bizkaia, Spain
josu.jugo@ehu.es

Abstract

When a vibration suppression adaptive algorithm is implemented to enhance an AMB based system, a good frequency measurement or estimation of the synchronous rotation is essential [1]. In this paper, two frequency disturbance rejection methods applied to the frequency sensor measurement are compared. The first method is based on the use of a Kalman Filter (KF) and the second is the implementation of a Frequency Locked Loop (FLL). Both have advantages and disadvantages related to the available hardware, noise type of the sensor, the fact of vibration minimization and the computational cost of the adaptive algorithm. Finally, experimental proofs in a laboratory testbed, based on the *MBC500 Rotor Dynamics*, show the effectiveness of each method.

1 Introduction

In the mechatronics field, the need of high precision in the measured variables is more and more common, specially when these signals are being utilized to the implementation of control techniques with more efficiency.

There are situations in which the sensors of the devices do not satisfy the needed specifications and the use of new hardware or the application of signal processing is necessary to counter this lack.

In particular, in machines with rotors, such as engines, milling machines, pumps,... the obtaining of a precise measure of the rotation frequency is very convenient, not only because it has a notorious influence in their behavior but also because it may be utilized to the application of active control.

Generally the lack of precision of sensors, as frequency ones, is due to they are affected by noise. In that cases, although there are different techniques to estimate accurately the required parameter, the most common in control field is the use of a Kalman Filter (KF) [2, 3].

On the other hand, in order to estimate the rotational frequency of the devices with rotors, it is possible to take advantage of their natural behavior, because the perturbation which is generated by the spinning of the rotor is a sinusoid synchronous with the rotation frequency. Hence, it is enough with estimate the position signal to know the frequency.

There are various methods to find the parameters of a sinusoid like its frequency, even if it is affected with noise, for instance, by means of an identification as it is performed in [4] or by means of a Frequency Locked Loop (FLL). The last possibility, which is profusely used in Radio Frequency field [5, 6], is applied to lock two signals, more than to estimate the frequency. However, in the case of machines with rotors, it may be used to lock a designer generated sinusoidal signal with the position signal, obtaining the actual frequency of rotation.

One type of devices with rotors which are very interesting owing to their natural advantages are those which are equipped with Active Magnetic Bearings (AMB). These elements have the property of allow an active control and, therefore, the perturbations generated by the spinning can be avoided.

There are different methods to apply to the AMBs to perform this vibration suppression and in the most of them an accurate measure of the frequency is required.

In particular, in this paper, the Adaptive Feed-Forward Vibration Controller (AFVC) presented in [1] is implemented to reduce the vibration. This algorithm, is based on the addition of signals with the same amplitude and frequency but in counterphase respect to the perturbation. In this way, the algorithm adapts the amplitude and phase of the signal, but a good measure of the frequency is a requirement.

To achieve an acceptable value of the measured frequency, two methods are proposed. Firstly, the use of a

KF to counter the noise of the sensor and secondly the implementation of an FLL to lock in frequency the AFVC generated signals with the measure of the position (notice, that with this method the frequency sensor will not be strictly necessary, as it is to use the KF). Both of them are studied under two different noise types: White noise and non zero mean white noise.

Finally, the two techniques are applied experimentally in a laboratory setup based on the *MBC500 Rotor Dynamics* of Launch Point technologies achieving a noise reduction or a frequency estimation which allows the utilization of the AFVC.

The outline of the paper is the following:

Firstly the synchronous vibration problem is stated in the section 2. Here, the solution based on the use of the AFVC is explained and the necessity of the implementation of a resettable time is concluded. Secondly, the testbed is described in section 3. Then, the implementation and the experimental results when applying the KF-based and FLL-based noise rejection are presented in section 4 and 5 respectively, followed by the interpretation of the obtained results in the section 6. Finally, the conclusions in the section 7 end the paper.

2 Problem statement

All the devices equipped with rotors present a synchronous vibration provoked usually by the non correlation between the center of mass and the main rotation axis. Generally this effect is minimized adding masses properly trying to fit the C.M. and the main axis of inertia. However, even with a very precise fitting, the centrifugal force which is generated becomes relevant when high speeds are required. For instance, in a machine with a $1Kg$ shaft, if the error between the position of the C.M and the rotation axis is $10^{-5}m$, when rotating at $500Hz$, the generated force is $1Nw$.

This perturbation can be minimized in the AMB based devices, owing to the active nature of those.

2.1 Frequency in the Adaptive Feed-Forward Vibration Controller

One of the techniques which exploits this feature, widely applied in the literature [1, 7], is the Adaptive Feed-Forward Vibration Controller (AFVC). This method is based on the generation of one sinusoid which acts in counterphase with the signal provoked by the unbalance,

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

In general, the parameters of (1) which are being to be adapted will be the amplitude (A_{x1}) and the phase (φ_{x1}), actually, by means of the amplitudes A_{1x1} and A_{2x1}. Since the frequency is not adapted, an accurate estimation of it is essential if a effective counteraction is needed.

The error in the measure of the frequency could be of different types, being the most commons the white noise and the non-zero mean white noise.

Two alternatives are proposed to lead with this problem, one based on the use of a KF and the another one on a FLL.

2.2 The resettable time

Since the AFVC utilizes the $sin(\omega t)$ and $cos(\omega t)$ to counter the vibrations, if the time value is large, the frequency noise is augmented and can degrade the generated sinusoid.

For example, the Fast Fourier Transform (FFT) of the produced signal when the shaft is rotating at $35Hz$ without time reset is shown in Fig. 1. It is clearly noticed that the AFVC cannot work properly with this signal

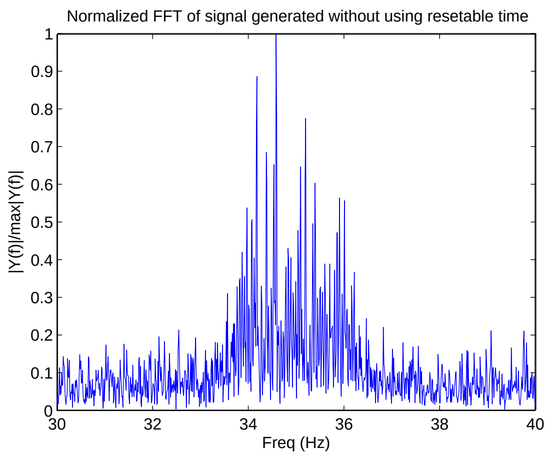


Figure 1: Normalized FFT of the signal generated without using resettable time

To avoid this problem, a resettable time is implemented. A basic algorithm to design a time block with reset is a resettable integrator with an unitary input signal. However, in the case of study, the time reset cannot be in any moment because this fact will change the phase of the generated sinusoid. Thus, only when the cosine of the signal takes a value approximate to one, it can be ensure that the time will be near to $0+2k\pi$, being the moments to reset the time. To lead to this, a counter and a comparison with the signal are required, following the scheme shown in Fig. 2

This block is interesting to minimize the effect of the frequency error and, then, it has to be present either with

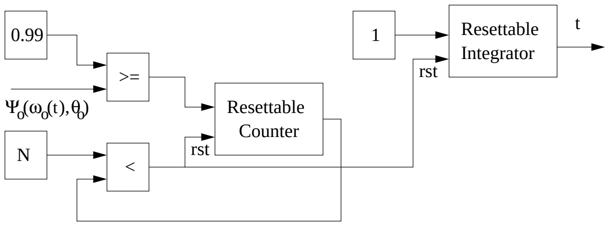


Figure 2: Resettable time scheme

the frequency noise rejection based on the KF or on the FLL.

On the other hand, in the experimental setup the capacity of the signal processor must be taken into account because it is in charge of the controller to ensure the levitation, of the rotation speed controller, of the adaptive vibration control and, in this case, of the frequency noise rejection. In this manner, a low cost algorithm for real frequency estimation could be a requirement.

3 Experimental setup

The testbed in which the experiments have been performed is based on the AMB system *MBC500 Rotor Dynamics* of Launch Point technologies, which is a laboratory device specially designed for research purposes [8]. It is composed of two AMBs and a rotor which includes an air turbine drive, allowing speeds up to 22000 rpm. As is schematically shown in Fig. 3, the shaft position is measured by Hall effect sensors and the currents, causing the forces in the bearings to maintain the hovering state, are driven by voltage amplifiers. Thus, the system inputs are the voltages given to the amplifiers, and the outputs are the voltages provided by the position sensors [9]. Finally, the testbed is completed by closing the loop with a stabilizing controller, which feeds back the system response appropriately. The implementation of the real-time discrete controller requires a suitable hardware, in this case the Digital Signal Processor (DSP) *DS1003* of dSPACE is used.

In this paper, this controller is the combination of a stabilizing controller, the rotation speed controller, the AFVC with the resettable time and one of the proposed frequency noise rejection algorithm.

4 Kalman filter based noise rejection

4.1 Implementation

The first option is the implementation of one KF just following the sensor, because the KF is able to estimate a variable affected by an stochastic perturbation using previous measurements and estimates of the variable. Its implementation is based on three main blocks, the One Step Predictor, the Kalman Gain Computer and the Riccati Equation Solver [10] as is presented in the Fig. 4.

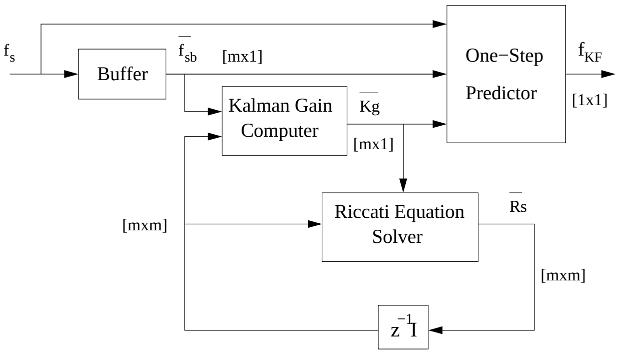


Figure 4: KF based frequency estimator scheme

The containing of each block is described by the equations (2), (3) and (4), respectively, while the terms between square brackets denote the dimension of the wire which links one block with the other.

Hence, the Kalman gain computer is represented as follows

$$\overline{Kg} = \frac{\overline{Rs} * \overline{f_{sb}}}{\sum_i \overline{f_{sb_i}}' (\overline{Rs} * \overline{f_{sb}})_i + k} \tag{2}$$

where $\overline{Kg}$ is the Kalman Gain matrix of dimension $mx1$, $\overline{Rs}$ of dimension mxm, the solution of the Riccati equation, $\overline{f_{sb}}$ of dimension $mx1$ the buffered terms of the input frequency and k a designer choice constant. The subscript i is referred to the element i of the corresponding array of $mx1$ elements and $'$ represents the conjugate of the term.

The Riccati Equation Solver is implemented by this equation:

$$\overline{Rs} = z^{-1}\overline{Rs} + \overline{Q} - \overline{Kg}(z^{-1}\overline{Rs} * \overline{f_{sb}})^H \tag{3}$$

here, z^{-1} is the one period delay operator, the superscript H is the hermitian operator and $\overline{Q}$ of dimension mxm, the correlation matrix of the process noise.

Finally, the task of One Step Predictor, which is to compute the noiseless frequency, corresponds to this formula:

$$f_{KF} = \sum_i \overline{f_{sb_i}}' \frac{\overline{Kg}_i (f_s - f_{KF})}{1 - z^{-1}} \tag{4}$$

with f_{KF} the desired noise rejected signal and f_s the last measure of the frequency acquired by the sensor.

Notice, that the computation of the KF may be heavy if m is large. Then, it has to be chosen properly.

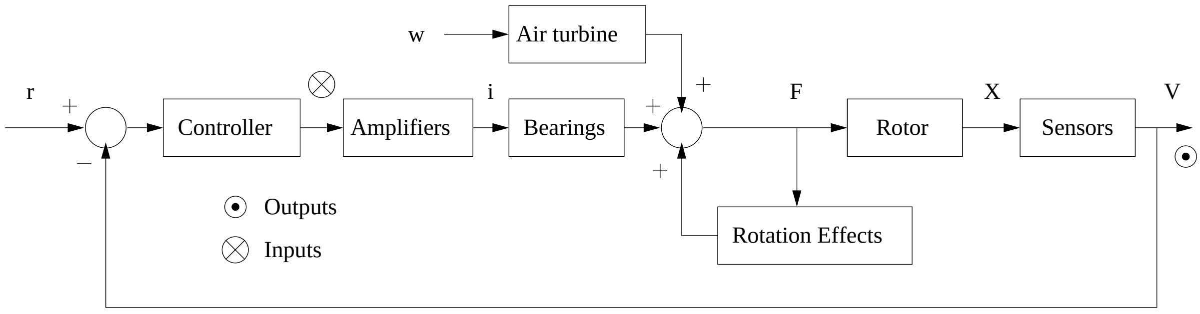


Figure 3: MBC 500 Rotor Dynamics scheme

4.2 Experimental Results

The KF algorithm is implemented in the dSPACE with $m = 2$ and $k = 3 \cdot 10^5$, and two different proofs are realized. Firstly, the vibration suppression is performed utilizing the KF to reject the frequency sensor white noise and secondly, to reject the same noise adding $-1Hz$ mean error. Both experiments are realized with the shaft rotating at $\sim 35Hz$.

The results of the first experiment, in concerns to the noise rejection are presented in the Fig. 5, where the sensor's measured frequency error of about $\pm 4Hz$ is reduced to an error of about $\pm 0.5Hz$. Due to this, the AFVC algorithm is able to reduce the vibration in more than a 50%, as is shown in the Fig. 6.

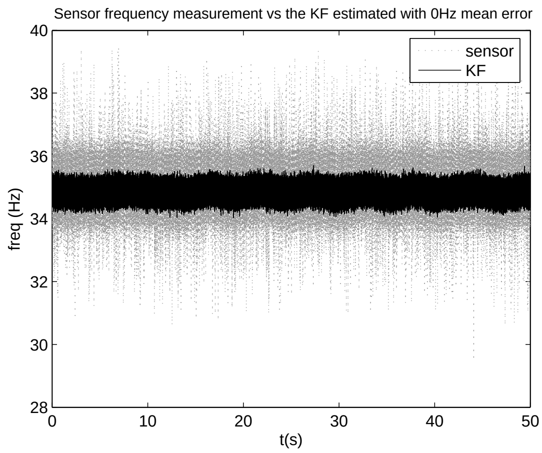


Figure 5: KF based noise rejection with $0Hz$ frequency mean error

On the other hand, when the second experiment is performed, the KF-based method cannot deal with the error of $-1Hz$ in the mean (Fig. 7), hence, there is a difference between the actual and the measured frequencies and the AFVC is unable to reduce the vibration.

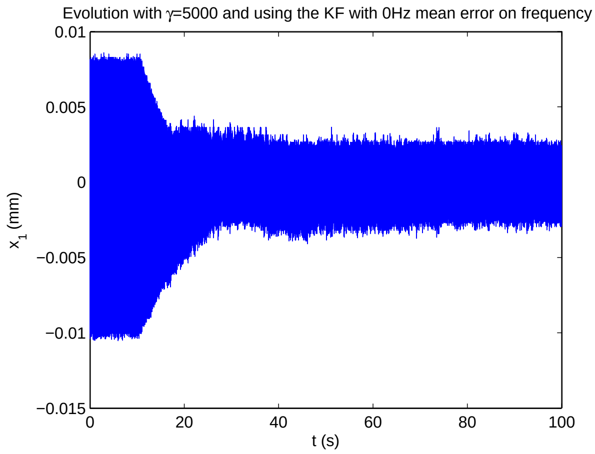
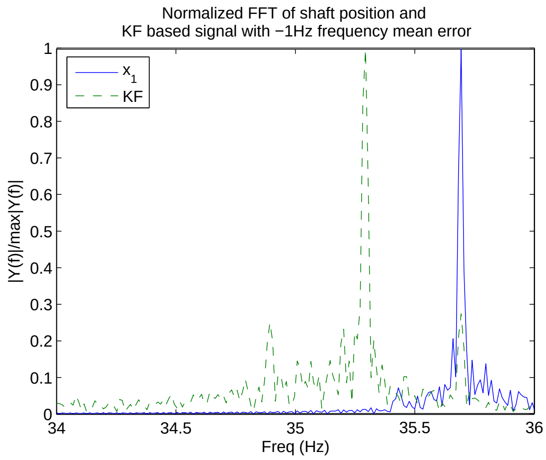


Figure 6: KF based vibration reduction with $0Hz$ frequency mean error

5 Frequency locked loop based noise rejection

5.1 Implementation

The FLL method takes advantage of the naturally generated synchronous vibration, i.e. since the rotation frequency has to be the same as the vibration's one, the measurement of the position can be utilized to estimate the actual rotation frequency. In fact, with this method, the frequency sensor is only utilized to control the rotation speed but it is not implied into the adaptation and can be a good first step to get a frequency sensorless device.
The basis of a FLL is the same of the PLL (Phase Locked Loop) [11] and consists on generate a frequency variable sinusoid in such a way that this frequency changes when it is compared with the position rotor output. The stationary state is achieved when both signals are locked on frequency. The difference between a PLL and a FLL is that the error between frequencies has to be multiplied by the time.



(a)

Figure 7: Sensor vs KF with $-1Hz$ frequency mean error

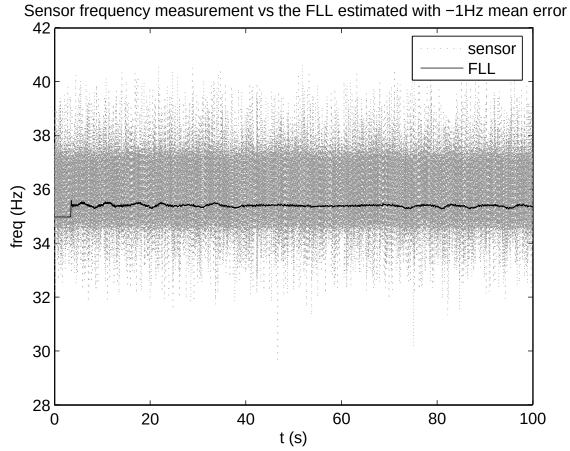


Figure 10: FLL based noise rejection with $-1Hz$ frequency mean error

In more detail, the FLL is composed by three main blocks, the frequency detector, the low pass filter and the Voltage Controlled Oscillator (VCO), as it is presented in Fig. 8. There are many options to implement each block and in the case of this paper there have been chosen as follows:

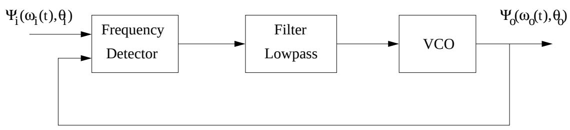


Figure 8: General scheme of an FLL

The frequency detector is the product between the reference $\psi_i(\omega_i(t), \theta_i)$ and output $\psi_o(\omega_o(t), \theta_o)$ sinusoids, in such a way that, when their frequencies are the same, the direct component of the output signal is null.

$$sin(\omega_i t)cos(\omega_o t) = \frac{1}{2}[sin(\omega_i + \omega_o) + sin(\omega_i - \omega_o)] \quad (5)$$

Expressing $\omega_o = \omega_i - \Delta\omega$ and supposed $\Delta\omega$ small, then, (5) can be rewritten as,

$$sin(\omega_i t)cos(\omega_o t) = \frac{1}{2}[\Delta\omega + sin(2\omega_i - \Delta\omega)] \quad (6)$$

In this manner, the direct component of the signal, is proportional to the error between frequencies, being zero when $\omega_i = \omega_o$.

As there is stated with the frequency detector, the oscillatory component of the signal has to be neglected. To lead with this fact, the lowpass filter (7) is designed.

$$F = \frac{0.0002493z^2 - 0.0004986z + 0.0002493}{z^3 - 2.994z^2 + 2.989z - 0.9944} \quad (7)$$
$$with\ T = 1/12000$$

The third component is the VCO. It is in charge of the generation of the sinusoid taking into account the signal provided by the lowpass filter. As is stated above, the main difference between a PLL and a FLL is that the last has to multiply the error signal by the time. This fact requires the development of a resettable time, in order to do not amplify the noise of the frequency error when the time is large. Moreover, these time resets demand a more robust controller than usual, to guarantee the stability and in this paper's case, a PID is designed. This controller, cancels the error in the permanent achieving the lock between the two signals and gives a measure of the frequency error $\Delta\omega$.

A complete block diagram of the FLL is presented in the Fig. 9.

Its operation is easy to follow. When the two waves pass through the frequency detector and the lowpass filter, a signal proportional to the frequency error is achieved. Then, it is given to the VCO which changes the frequency of the output sinusoid. By means of the action of the PID, the error between the signals goes to zero and the lock is carried out.

5.2 Experimental Results

The same experiments that have been performed to prove the effectiveness of the KF-based noise rejection method are realized with the FLL-based method, but in this case only the second one is presented, because, since it is more challenging, the first one has to be fulfilled if this is successful.

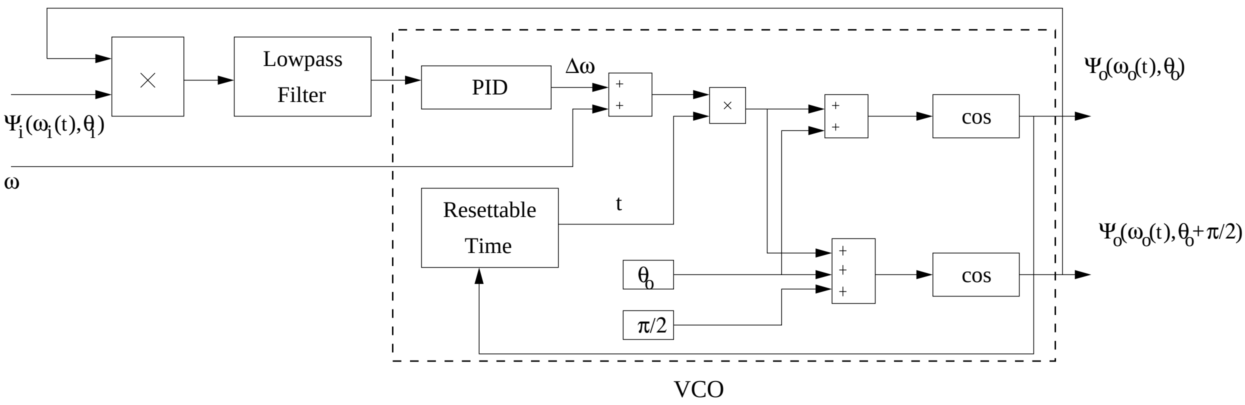
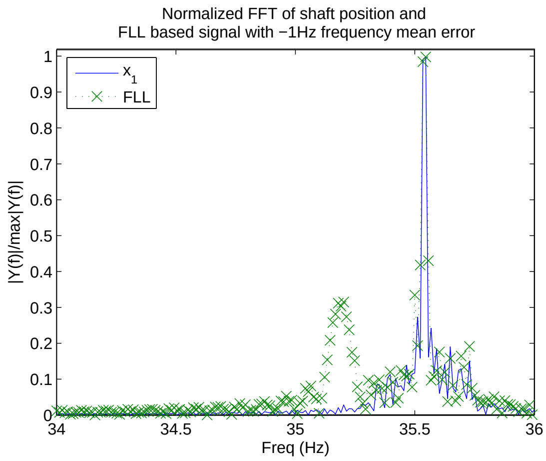


Figure 9: Complete block diagram of the implemented FLL



(a)

Figure 11: Sensor vs FLL with $-1Hz$ frequency mean error

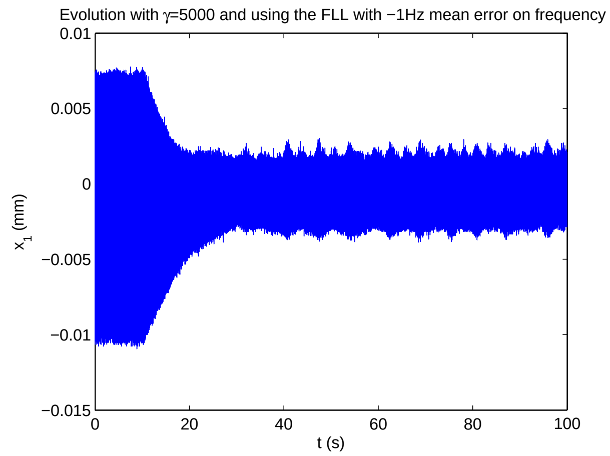


Figure 12: FLL based vibration reduction with $-1Hz$ frequency mean error

Hence, in the Fig. 10 the measured frequency and the FLL observed frequency are presented with the shaft rotating at $\sim 35Hz$. It is clear that the frequency measured by the sensor has the mean at $36Hz$ and an error of $\pm 4Hz$ while the frequency estimated by the FLL has the mean at $\sim 35.5Hz$, which is the actual rotation speed (Fig. 11), and only with an error of $\pm 0.25Hz$.

Therefore, in the Fig. 12 it is shown the effectiveness of the combination of the AFVC with the FLL, achieving more than a 50% of vibration reduction.

6 General Results

The main advantages of the FLL-based method compared with the KF-based one are, first, the possibility of lead, not only with the frequency sensor's white noise, but also with the mean error value (Figure 12), and, second, the less computational cost. One of the reasons of this, is that the FLL generates the sinusoids which are necessary for the adaptive algorithm (1) naturally, while a sinusoid generator has to be added when the KF is implemented. Moreover, the KF is also computer's resources consuming when state dimension m is large. In fact, with the hardware utilized in this study, the possible maximum state dimension is 2, hence, the noise reduction is not the best that could be achieved with a KF method. However, this dimension is enough to accomplish the necessary estimation of the frequency to apply the adaptive algorithm (Figure 6).

On the other hand, the main advantage of the KF-based vs the FLL-based method is that it only depends on the sensors lectures and its behavior is not conditioned, as it is in the FLL, by the position signal i.e. the FLL needs the rotor position sinusoid signal to work properly, and this fact has to be considered when this signal is reduced completely or if the adaptation is very fast, producing a non-sinusoidal output.

Another fact which deserves a study is the need of the sensor.

Regarding to the FLL-based method, the frequency sensor is not necessary because the FLL estimates the rotation speed taking into account the generated vibration. However, its implementation is essential in the KF-based method, as it is utilized in this paper. In any case, it is also possible to reject the noise of the position signal with the KF and use it to implement the AFVC technique.

7 Conclusions

In this paper, two methods to reject the noise of the frequency sensor which measures the angular speed of the spinning rotor in a laboratory setup based on the *MBC500 Rotor Dynamics* are presented. This machine is equipped with two AMBs and then, it is possible to implement an active control to minimize the vibrations which are naturally generated when the shaft is rotating.

The method applied to achieve this reduction is the AFVC, but the algorithm by itself is not enough to counter these vibrations, due to the difference between the actual and the measured rotation frequency, since it is not in charge of adapt this parameter. In this manner, one of the proposed techniques and a resettable time have to be implemented.

With both methods, the KF and the FLL, a vibration reduction of more than 50% is obtained, but each one has advantages and disadvantages according to the type of noise it can reject, the computational weight it consumes, the requirement of the sensor or the fact that the position signal has not sinusoidal shape when the perturbation is countered.

Therefore, the KF is a better solution when a complete reduction is desired because the frequency estimation does not depend on the position lecture or if a fast hardware is available to implement the complete control scheme (levitation controller, rotation speed controller, AFVC, resettable time, KF and sinusoids generator or FLL).

On the other hand, the FLL achieves good results when the noise has non-zero mean or when a low computational cost is necessary.

As future development of the investigation there are, to improve the FLL algorithm to allow its use even if the position signal is very small, the obtaining of a sensorless AFVC scheme for machines with AMBs and the use of other techniques of computation optimization [12], in order to enhance the system with a higher dimension KF.

8 Acknowledgments

The authors are very grateful to the CICYT for the support of this work, through projects DPI2002-04155-C02-01 and PTR95-0897.OP.CT and to the Basque Government for financing the project IT-208-07, and the Predoctoral grant BF104.466.

References

[1] K. Nonami and Z. Liu, "Adaptive unbalance vibration control of magnetic bearing system using frequency estimation for multiple periodic disturbances with noise", in *Proceedings of IEEE Conf. Control Applications*, Hawaii (USA), 1999.

[2] b. Seong-Joon L. Sang-Wook, L. Jun-Seok and S. Koeng-Mo, "Time-varying signal frequency estimation by vff kalman filtering", *Signal Processing*, vol. 77, pp. 343–347, 1999.

[3] B. F. La Scala and R. R. Bitmead, "Design of an extended kalman filter frequency tracker", *IEEE transactions on signal processing*, vol. 44, pp. 739–742, 1996.

[4] A. Kremlev N. Nikolaev S. Aranovskiy, A. Bobtsov and O. Slita, "Identification of frequency of biased harmonical signal", in *Proceedings of the 9th IFAC Workshop ALCOSP'07*, Saint-Petesburg (Russia), 2007.

[5] K. Clarke and D. Hess, "Frequency locked loop fm demodulator", *IEEE Transactions on Communications*, vol. 15, pp. 518–524, 1967.

[6] Sawan A. Djemouai and M. Slamani, "A 200 mhz frequency-locked loop based on new frequency-to-voltage converters approach", in *Proceedings of the 1999 IEEE International Symposium on Circuits and Systems, 1999. ISCAS '99*, Orlando, FL (USA), 1999.

[7] J. Shi, R. Zmood, and L. Qin, "Synchronous disturbance attenuation in magnetic bearing systems using adaptive compensating signals", *Control Engineering Practice*, vol. 12, pp. 283–290, 2004.

[8] I. Arredondo, J. Jugo, and V. Etxebarria, "Modelling of a flexible rotor MagLev system", in *Proceedings of 2006 American Control Conference*, Minneapolis, Minnesota (USA), 2006.

[9] LaunchPoint, *MBC500 Magnetic Bearing System Operating Instructions*, Goleta, CA (USA), 2002.

[10] S. Haykin, *Adaptive Filter Theory*, Prenitice Hall, Inc, Englewood Cliffs, New Jersey (USA), 1986.

[11] W. F. Egan, *Phase-Lock Basics*, Jon Wiley & Sons, Inc., New York (USA), 1998.

[12] J.Jugo and I. Arredondo, "Adaptive control for attenuating vibrations using nonuniform sampling", in *9th IFAC Workshop ALCOSP'07*, Saint Petersburg (Russia), 2007.