

FORCES ESTIMATION IN THE TURNING PROCESS USING VIBRATION MEASUREMENTS

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Abstract. *The knowledge of the manufacturing forces is useful in the cut processes to monitoring purposes. Unfortunately, the direct forces measurement is not so easy in a real time productive process monitoring. It is occurred due to the dimensions of the transducers and difficulties of them assembly. In these cases indirect measurements techniques can be used to monitoring purpose. In this work the viability of the use of indirect identification forces by vibration measurements in a turning process was studied. Through acceleration measurements at the vertical directions of the cutting process, a classical frequency domain procedures and a time purposed technique, based on single value decomposition, were tested. A good agreement was observed when the Power Spectrum Density PSD of the estimated forces was compared with the measured vertical forces with a Kystler dynamometer one. Expected errors on estimated PSD at anti-ressonance regions for indirect identificated forces in time domain were obsered such as ressonance errors in frequency domain.*

Keywords*: estimated forces, turning process, signal vibrations, identification techniques*

1. INTRODUCTION

The determination of the force components that act in the cutting edge during manufacture process has been shown very important as well of the application purpose as of the research one “Souza (2004)”.

The knowledge of the manufacture force and the study of its components behavior is very important not only because the required power to execute the cut, but due the fact that it might be considered in the projects of the machines tools and its elements. In other way, it can be responsible direct for the collapse of the tool of cut by edge plastic deformation, beyond influencing in the development of other wearing mechanisms and processes “Rocha and Silva (2004)”. The cutting forces measurement is efficient in the detection of transitory failures in the tool edges. In general, a fast change of the signal amplitude forces level is a symptom of crack or breaking of tool. “Souza (2004)”.

There are specific situations were the manufacture force can be measured directly with force transducers “Silva (2000)”. However, due to the dimensions of the transducers and difficulties of fast assembly, the direct force measurement is limited at research and specific applications. To real time monitoring purpose indirect identification force techniques must be used to avoid the assembly problems.

There are same different ways to estimate indirectly the cutting forces, such as electrical power, torque and deflection tool measurements “Souza (2004)”. One other approach can be based on vibration measurements which are very used on structural applications “Silva (2000)”. The advantages to use vibration monitoring are: low cost sensors, not intrusive setup, large frequency analysis range and a very well knowledge signal analysis background “Meola (2004)”.

The force estimation by vibration analysis is based on vibration measurements and the dynamic response of the system compounded by the workpiece, tools, structural elements machine, in short: overall tool machine. Several types of dynamics models can be used in force estimation, such as: a set of response functions in frequency (FRFs), Impulsive Response Function (IRFs), auto-solutions (natural frequencies, modal damping factor, generalized mass and Modal Vectors) or still a structural models represented by inertia matrices, rigidity and damping “Silva (2000)”, normally based on a pseudo inverse technique.

Procedures of identification of forces in the frequency and the time domain can be used. The techniques in the frequency domain search to determine the spectrum of the input exciter forces using the spectrum of the vibrations outputs and the cross frequency response functions, obtained by a SIMO, MISO or MIMO FRF estimator “Bendat and Piersol (2000)”. At the time domain it is used vibration data with a deconvolution technique. Both the techniques will be tested in this work.

2. OBJECTIVE

The objective of this work is the study of the indirect cutting force estimation in a turning process of a ABNT 1045 steel bar, using acceleration measurement signals and indirect force identification techniques in the time and frequency domain.

3. METHODOLOGY

For the development of this work, the Laboratório de Ensino e Pesquisa em Usinagem (LEPU) of the Universidade Federal de Uberlândia (UFU) supplied a turning machine made by ROMI. A cemented carbide tool of type SPUN120308 with a TIN recovering was used. The two cutting conditions that were used to turning an ABNT 1045 steel bar are presented at Tab. 1. The external diameter of the steel bar was of 78.5 mm., and a dry cutting condition was used.

Table 1. Cutting Conditions

	Condition 1	Condition 2
Cutting Speed (m/min)	345	345
Depth of cut (mm)	1.5	1.5
Feed-rate (mm/rev)	0.138	0.298

Vibration signals and force signals were acquired for both cutting conditions. The vibration signals had been gotten for the development of the indirect cutting force identification. The direct measurement of this force had been purposed to comparing the gotten results and validating the methodology.

The vibration signals had been acquired with a frequency of 8192 Hz. The signal was sampled during 10 seconds in the frequency band between 10 Hz and 3 KHz. The instrumentation setup was composed by:

- One B&K signals conditioner type 2692;
- One notebook;
- One piezoelectric accelerometer type 4371;
- One A/D National Instruments, USB 9162;
- One B&K accelerometer calibrator, type 4294, (10 m/s^{-2} RMS level at 159.2 Hz).

The force signals had been acquired with a frequency of 8192 Hz during 4 seconds at each test. The instrumentation setup was composed by:

- One Signals conditioner Kistler, type 5019;
- One notebook;
- One dynamometer Kistler, type 9265B;
- One A/D National Instruments, BNC 2110;

The data acquisition schema is showed on Fig. 1.

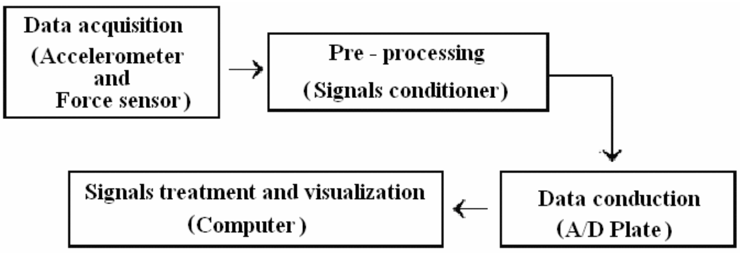

Figure 1. Data acquisition schema..

The force and acceleration sensors position are indicated on Fig. 2.

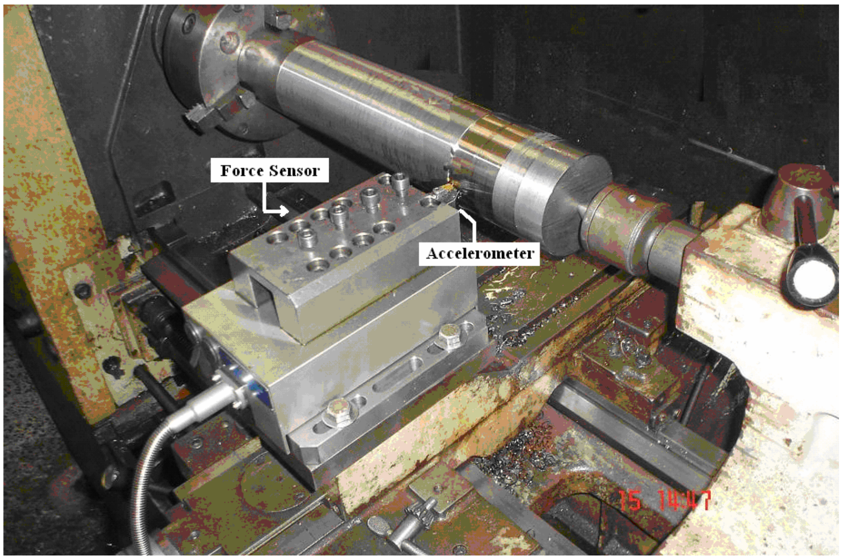

Figure 2. Force and vibration sensors position.

The indirect force estimation by vibration monitoring implies in the use of the Frequency Response Function FRF and the Impulsive Response Function IRF at the frequency and time domain respectively. The impulsive force was applied using a B&K impact hammer, type 4294 with a plastic tip (0-2000 Hz) and the acceleration response was measured with a 4371 B&K piezoelectric accelerometer. The signal was sampled with a frequency of 16384 Hz. The FRF was gotten using 100 samples and the H1 estimator. The impulsive force was applied at the tool tip at vertical direction, the same preferential direction of the accelerometer how is showed in Fig. 2. The FRI was obtained by inverse Fast Fourier Transform of the FRF.

The methodology of indirect force estimation on frequency domain is based on direct inversion of the FRF matrix and its respective product with the vibration measured spectrum. Due to the fact that the FRF matrix is bad scaled usually the pseudo-inverse of it is used in accordance with the Eq. (1).

$$\{F(\omega)\} = [H(\omega)]^{+}\{X(\omega)\} \tag{1}$$

In Equation (1), $\{X(\omega)\} \in R^{N}$ is the amplitude frequency vector of the measured vibration response, $[H(\omega)]^{+} \in R^{N,N}$ is the pseudo-inverse of the matrix of FRFs and $\{F(\omega)\} \in R^{N}$ is the spectrum of the estimated forces.

The least square approach to the pseudo-inverse is given by Eq. (2).

$$[H(\omega)]^{+} = ([H(\omega)]^{T}[H(\omega)])^{-1}[H(\omega)]^{T} \tag{2}$$

Two problems occur when the frequency approach is used:

- Large error can be observed at resonance region (Silva, 2000).
- It is not can be used at real time applications.

The time technique is less sensible at resonances problems “Silva (2000)” and can be used at real time monitoring too. It is based on the deconvolution of the Dhuramel integral given by Eq. (3), where h(t) is the IRF, f(t) is the exciter force ate time t and x(t) it is the vibration amplitude response at time t. If the h(t) is the IRF of the acceleration, the acceleration response can be used in left side of Eq. (3).

$$x(t) = \int_{-\infty}^{\infty} h(t-\tau)f(\tau)d\tau \tag{3}$$

For physically realizable mechanical systems (causal) the IFR is null for all the values of t lower than 0 and the Eq. (3) it can be rewritten as the Eq. (4).

$$x(t) = \int_{0}^{t} h(t-\tau)f(\tau)d\tau \tag{4}$$

The discretization at Δt the sampling time of the Eq. (4) is given by Eq. (5).

$$x(k\Delta t) = \sum_{i=0}^{k} h[(k-i)\Delta t]f(i\Delta t)\Delta t \text{ , with } k=0,1,2,...,p\text{-}1. \quad (5)$$

In vectorial notation the Eq. (5) can be rewritten as:

$$x_k = \sum_{i=0}^{k} h_{k-i} f_i \text{ , com } k=1,2,...,n. \quad (6)$$

The expansion of Eq. (4) results in:

$$\begin{aligned} &\text{For } k = 0: && x_0 = f_0\, h_0 \\ &\text{For } k = 1: && x_1 = f_1\, h_0 + f_0\, h_1 \\ &\text{For } k = 2: && x_2 = f_2\, h_0 + f_1\, h_1 + f_0\, h_2 \\ &\text{For } k = p\text{-}1: && x_{p-1} = f_{p-1}\, h_0 + f_{p-2}\, h_1 + ... + f_0\, h_{p-1} \end{aligned} \quad (7)$$

In matrix notation, the Eq. (7) is given by:

$$\{x\} = [h]\ \{f\} \quad (8)$$

Using a minimum least square inverse, finally the estimated force can be obtained by:

$$\{f\} = ([h]^T[h])^T\ [h]^{-1}\ \{x\} \quad (9)$$

In accordance with the specifications of the Kistler dynamometer, type 9265B, the natural frequency of assembled device in the vertical direction is around 2500 Hz. Therefore, according to “Brüel & Kjaer (1980)”, the band of frequency response can be used of approximately 1/3 of the frequency of resonance of the assembled sensor. Then, in this work the upper frequency analysis is limited at 833 Hz. Therefore a low band pass filter with a cut off frequency of 800 Hz was applied at overall signal used in this work.

4. RESULTS

The signals of cutting force amplitudes measured by dynamometer in function of time at both conditions (Condition 1 and Condition 2 of Tab. 1) are showed in Fig. 3 and 4, respectively.

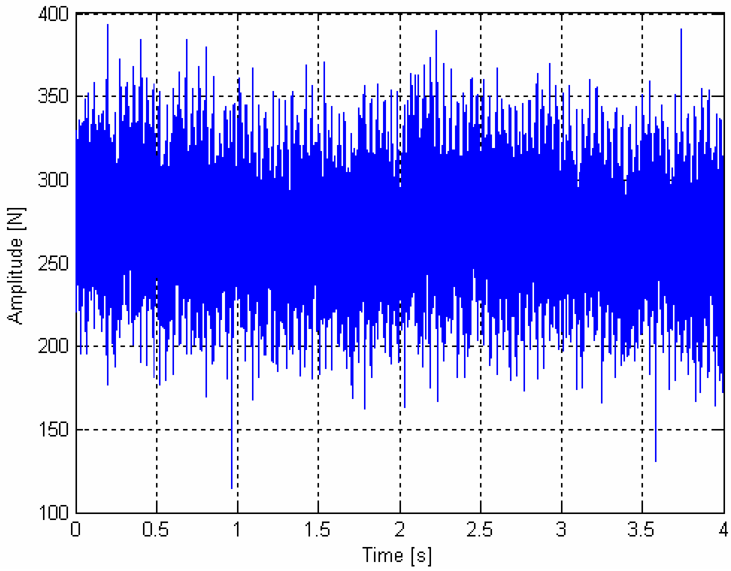

Figure 3. Cutting force amplitude in function of time at condition 1.

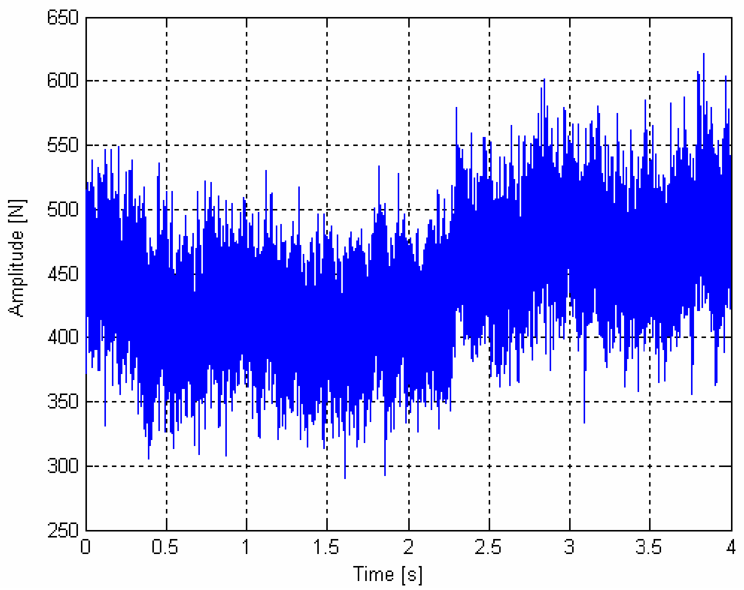

Figure 4. Cutting force amplitude in function of time at condition 2.

In Figures 3 and 4 is verified that the cutting force amplitude increased about 50% of the cutting condition 1 (feed-rate of 0.138 mm/rev) for the cutting condition 2 (feed-rate of 0.298 mm/rev). These results are in accordance with the theory, which consider that the increase of the force occurs proportionally with the increase of the feed rate. This fact also can be visualized in the frequency domain, where the force magnitude at condition 2 had an increase of about 10 dB when compared with the force magnitude at condition 1, as seen in Fig. 5.

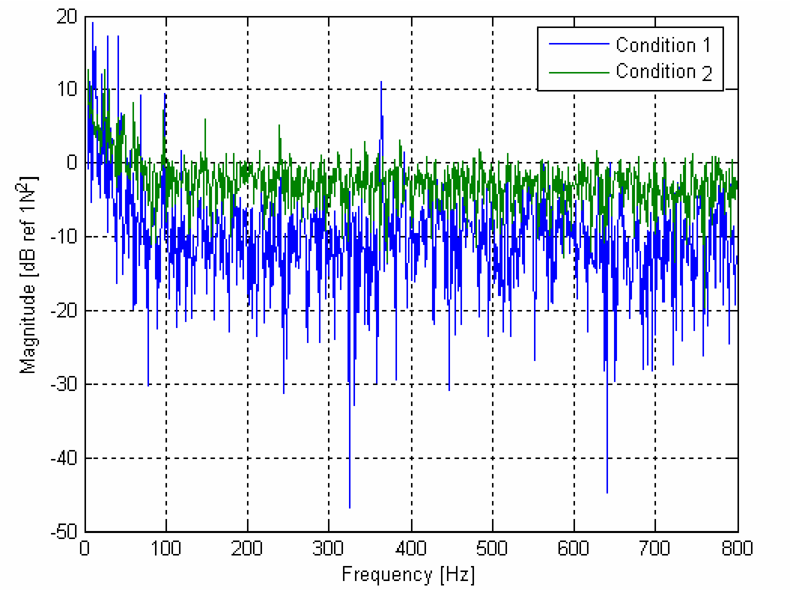

Figure 5. Power Spectrum Density of the cutting forces measured by dynamometer, at conditions 1 and 2.

The IRF amplitude of the system is showed in Fig. 6. It can be observed that the system is highly damped. So, for the force estimation using the deconvolution in time domain technique, presented in section 3, a discretization of p = 256 points was used.

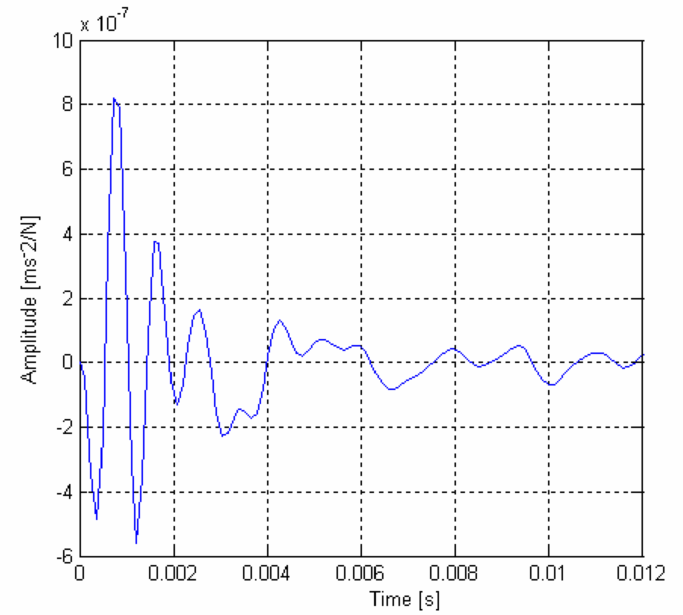

Figure 6. The Impulsive Response Function Amplitude.

4.1. Results of the Identification in Time and Frequency Domain at Condition 1.

The Power Spectrum Density of the cutting forces measured by dynamometer and estimated by the identification technique in time domain at Condition 1 is presented in Fig. 7.

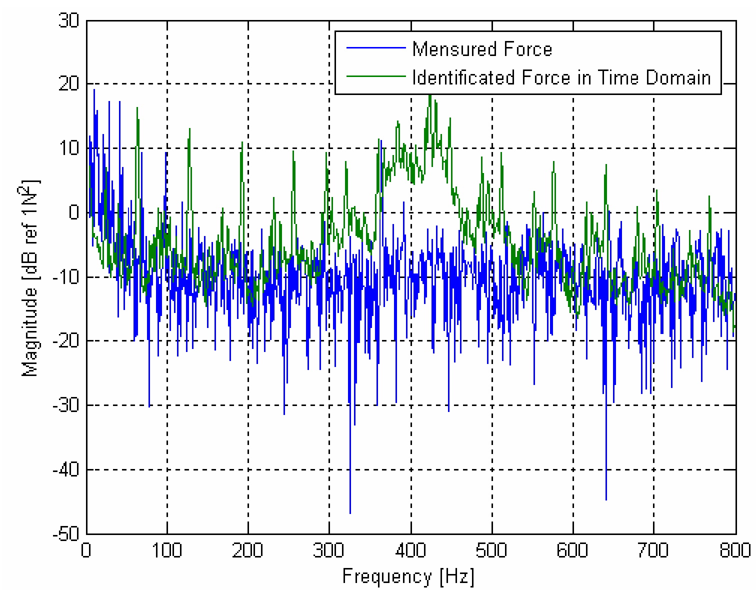

Figure 7. PSD of the measured and estimated forces in time domain, at Condition 1.

It can be verified in Fig. 7 that there are no explicit differences between the measured force magnitude and the estimated force magnitude, except in the anti-resonance region of the PSD, for example, around at 400 Hz. This region can be observed in Fig. 8, which represents the magnitude of the FRF of the studied system.

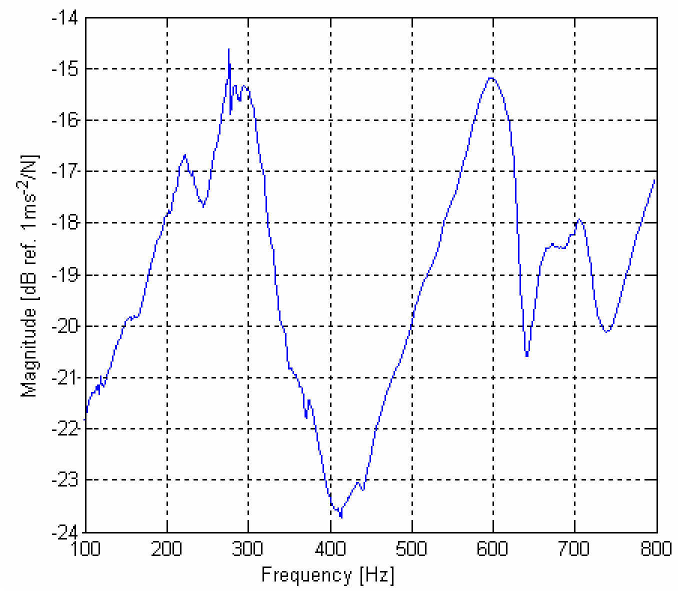

Figure 8. System Frequency Response Function (FRF).

In opposite of that occurred with the force identification result in time domain, it is observed for the force identification result in frequency domain, as seen in Fig. 9. It this figure can be observed that there is similarity in the values of magnitude only at anti-resonance regions, comparing the measured force with the identified force in frequency domain. At resonance regions a differences of approximately 15 dB can be observed at the region of 220 Hz and 20 dB at the region of 600 Hz, for example. The force identification errors in frequency domain that occurred at resonance regions were observed by "Silva (2000)".

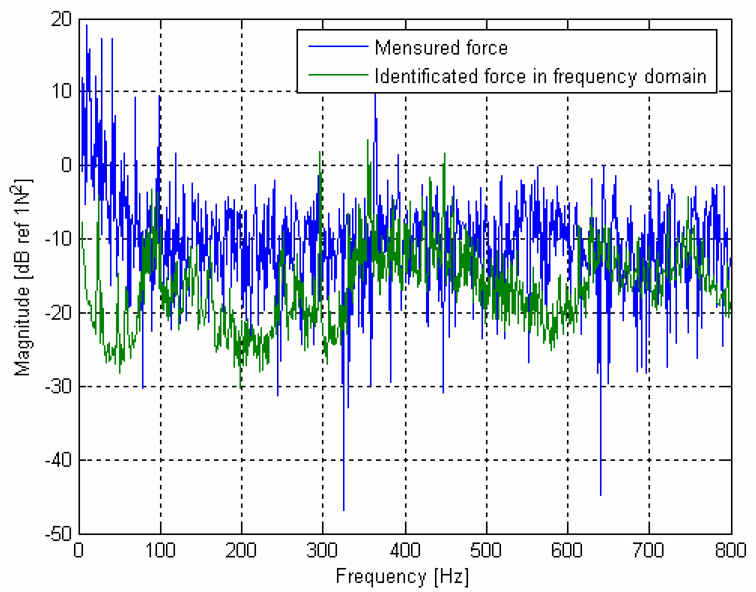

Figure 9. PSD of the measured and estimated forces in frequency domain, at Condition 1.

The occurrence of force identification errors in time domain at anti-resonance regions can be minimized through the application of several sensors in many positions. It happens due to the fact of the anti-resonances not vary with the sensors position changing.

4.2. Results of the Identification in Time and Frequency Domain at Condition 2.

The Power Spectrum Density of the cutting forces measured by dynamometer and estimated by the identification technique in time and frequency domain at Condition 2 is respectively presented in Fig. 10 and 11.

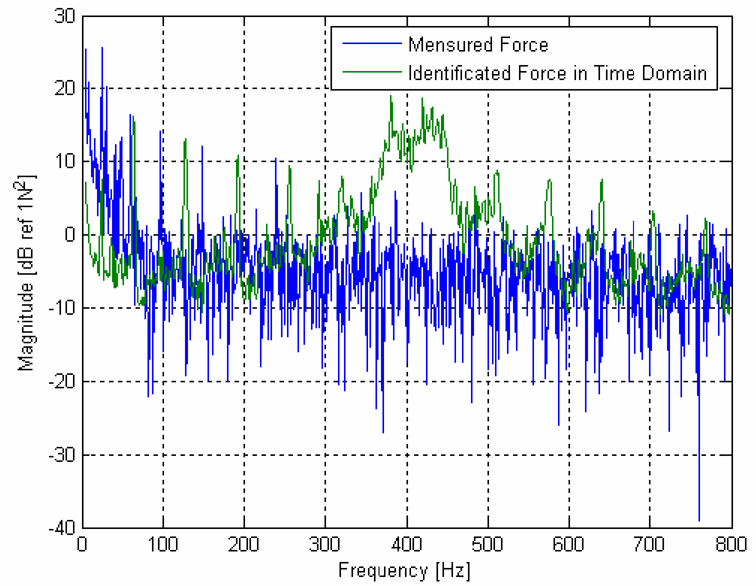

Figure 10. PSD of the measured and estimated forces in time domain, at Condition 2.

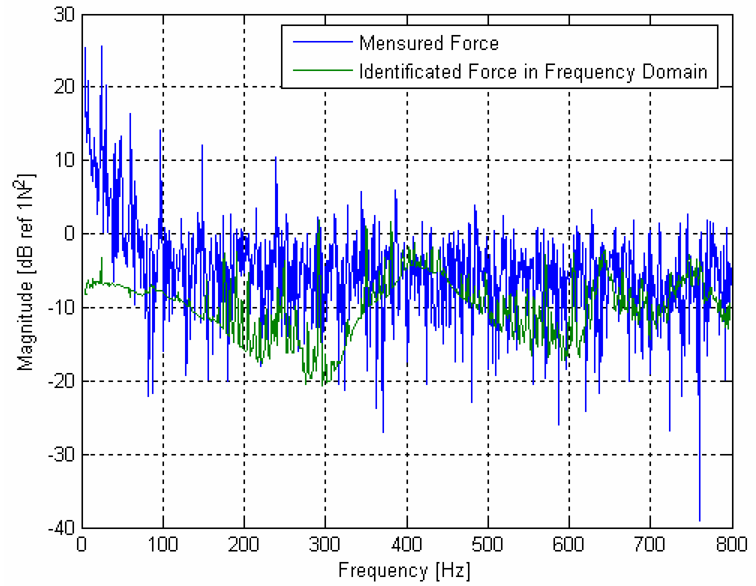

Figure 11. PSD of the measured and estimated forces in frequency domain, at Condition 2.

The obtained results for Condition 2 are most similarly to the ones of Condition 1 when the force measured by dynamometer is compared with the identified forces in both domains. It is observed in Fig. 10 and 11 that the anti-resonance regions for the force identification in frequency domain and the resonance regions for the force identification in time domain presented better results.

Figures 12 and 13 show the comparison of identified forces results for both cutting conditions, in the time and frequency domains, respectively.

It is observed in Fig. 12 that the force magnitude for the condition 2 (feed-rate of 0.298 mm/rev) is about 10 dB above of the force magnitude for the condition 1 (feed-rate of 0.138 mm/rev), except at anti-resonance regions. The results are coherent with the theory, which proposes that the cutting force increases with the increasing of the feed-rate. The fact of the force values be coincident at the anti-resonance is because of they are regions where there are identification errors in time domain.

Analyzing the Fig. 13, it is verified that there are differences about 40 dB at resonance regions, which present identification errors in frequency domain. However, at anti-resonance regions, the magnitudes are approximately different about 15 dB, such as it was predicted. It is due to the fact of the feed-rate increasing grows up the areas of the primary and secondary shearing plans, causing a linear proportionally increase of the manufacture force "Rocha and Silva (2004)".

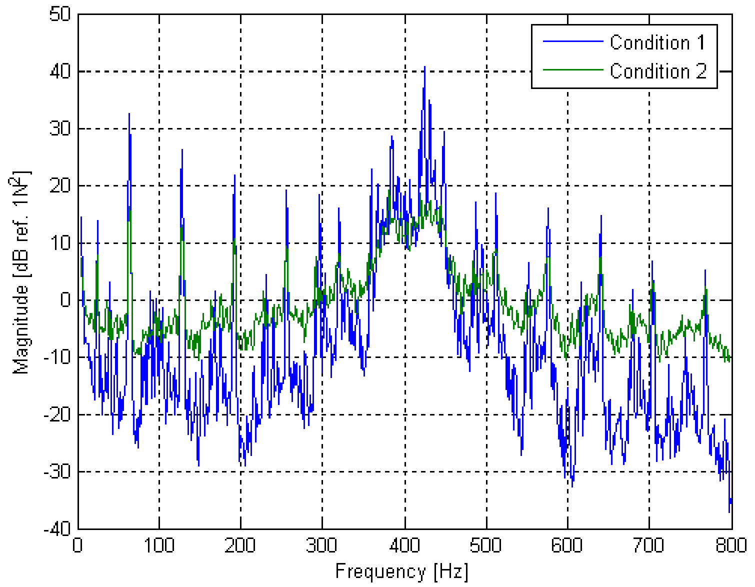

Figure 12. PSD of the estimated forces in the time domain at both cutting conditions.

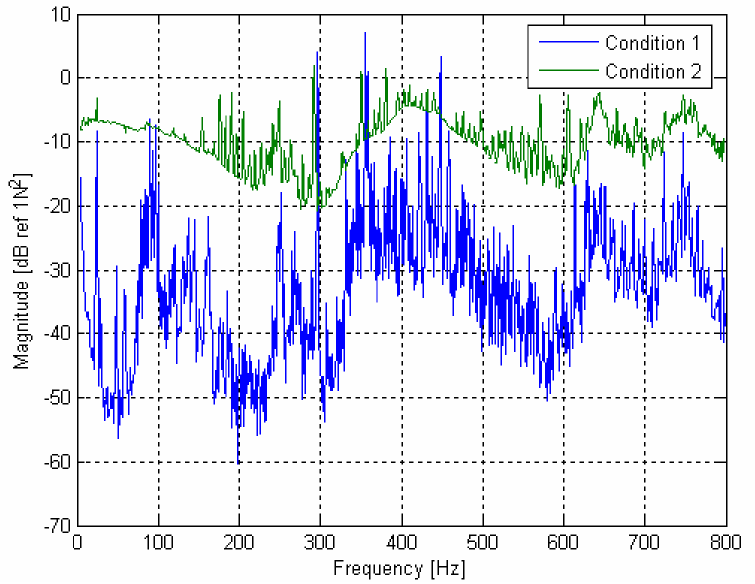

Figure 13. PSD of the estimated forces in the frequency domain at both cutting conditions.

5. CONCLUSION

The main conclusions of this work are:

- There were no explicit differences between the magnitudes of the measured forces and identified forces in time domain, except at anti-resonance regions of PSD for both cutting conditions.
- Comparing the measured force and the identified one in frequency domain, it was verified that there are similarity in the magnitude values only at anti-resonance regions, for both cutting conditions.
- Such as the forces measured directly by dynamometer as the identified forces in time and frequency domain presented increases in the amplitude and magnitude values with the increase of the feed-rate.
- The cutting force amplitude increased about 50% of the cutting condition 1 (feed-rate of 0.138 mm/rev) for the cutting condition 2 (feed-rate of 0.298 mm/rev), which are in accordance with the theory.

- The force magnitude for the condition 2 was about 10 dB above of the force magnitude for the condition 1, except at anti-resonance regions, where the values were coincident due to presence of errors in the force identification in the time domain.
- Comparing the results of identified forces for both conditions, differences of approximately 40 dB occurred at resonance regions, which presented identification errors in the frequency domain. However at anti-resonance regions, the differences were about 15 dB, in accordance with the theory.

It is necessary to point that the occurrence of identification errors in the time domain at anti-resonance regions can be minimized through the application of several sensors in many positions, once that the anti-resonance is a point FRF characteristic instead of the resonance which is a system property.

6. REFERENCES

Bendat, J. S. and Piersol, A. G., 2000. "Randon Data, Analysis and Measurements Procedures", John Wiley & Sons, ISBN 0-471-31733-0. pp 586.

Brüel & Kjaer, 1980. "Measuring Vibration". pp 40.

Meola, T., Duarte, M. A. V., Costa, e. S., Machado, A. R. " Tool Life Monitoring Drill´S Process Using Acoustics and Vibration Signals.", In: National Congress of Mechanical Engineering, 2004, Belém.

Rocha, A. M. and Silva, M. B., 2004, "Metal Manufacturing", 8ª edition, Uberlândia, Brazil.

Silva, L. A., 2000, "Force Identification Tecniques in Time Domain". Federal University of Uberlandia, Uberlandia, Brazil.

Souza, A. J., 2004, "Application on Multisensor approach for cutting tool-life prognostication in turning processes". Federal University of Santa Catarina, Florianopolis, Brazil.

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