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Methods for modal parameters identification applied to CNC machine tool feed drives

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Abstract

The paper presents a critical appraisal of existing methods for the identification of modal parameters (natural frequencies, damping ratios and mode shapes) for CNC machine tool feed drives. The classical methods for modal parameter identification are briefly discussed and the advantages of novel application of Continuous Wavelet Transform for modal parameter identification of CNC machine tools are underlined.

The evaluation of the state of the art of modal analysis techniques also contains a description of the main methods used in the modern experimental modal analysis applied to frequency and time domains. The accuracy of modal parameters (especially of damping ratios) identified from the measured frequency response function is influenced by various parameters and conditions, depending on which modal parameter extraction technique is used.

The conclusions of the critical appraisal of these methods will help the designers and academic and industrial researchers to develop and use methods which permit the calculation of modal parameters with high accuracy.

1 Introduction

The study of machine tool resonant frequencies plays an important part in ensuring the machine performance for a high bandwidth in the frequency domain under cutting and non-cutting conditions. The harmonic frequencies produced by cutting forces can coincide with the natural resonant frequencies of the machine and produce detrimental resonant vibrations. The CNC machine tools often lose stability by inadvertently exciting vibration modes whose frequencies are as high as five times their operating bandwidth. Whether a given vibration mode will cause instability depends very sensitively on its damping properties which is very difficult to predict.

There are numerous methods for determining the modal parameters (mode shapes, damping, resonant frequencies) of non-stationary signals, such as vibration or output signals generated by the encoders included in the CNC machine tool feed drives. Continuous Wavelet Transform proved to be more efficient compared to the classical method based on the transmissibility relation at resonance.

Modern experimental modal analysis software packages automatically identify the modal parameters from measured data. They use various methods in the frequency domain (global rational fraction polynomial method) or time domain. This paper is intended to be a survey based on the critical appraisal of the recent advances regarding the identification methods for modal parameters of CNC machine tools.

Classical methods for modal parameter identification

The assumptions made in modal analysis were mentioned by Gatzwiller [1]: linearity (the structural response can be described by linear second order differential equations), observability, time invariance, causality (only one mode at each pole location), stability, structural reciprocity and a global definition of the modes.

The essential stages of a modal test were enumerated by Ewins [2] (Figure 1):

- Apply a controlled excitation of the structure;
- Measure the excitation force and response levels;

- Derive the frequency response function (FRF) when FFT is applied to time data. The frequency at which maximum amplitude increases occurred could be determined from the time trace and the natural frequencies were ascertained from the FRF.
- Identify the modal parameters from measured FRF;
- Build the modal model of the test structure.

The modal analysis of rotating structures should consider several approaches:

- the use of stationary and / or rotating axes frames;
- the addition of gyroscopic effects;
- damping acting in both stabilising and de-stabilising ways;
- likelihood of non-linear behaviour;
- multi-frequency responses to harmonic excitation.

The strong link between the type of the stimuli and the results of a modal test was analysed by Verboven et. al [3] and the main conclusions were:

a) The most important structural modes corresponded to lower resonance frequencies;
b) The measurements using a multi-sine excitation have a less bias effect due to higher signal-to-noise ratio.
c) The type of excitation signal affects the damping ratios and the mode shapes.

Figure 1. The stages in elaborating a modal model [2]

The levels of forced and free vibration of non-linear dynamic systems are influenced by the damping. The various parameters (damping capacity, loss factor, Q-factor, damping ratio) which represent damping were mentioned by De Silva [4]. Also the author studied the damping models (viscous, hysterectic, structural and fluid) that characterise the nature of mechanical energy dissipation in the system and the principal characteristics of the most used damping measurement methods were shown in Table 1. The limitations to the use of damping values determined from experimental data were:

- the modal interactions from the resulting transient vibration were neglected because damping was assumed to be proportional with the desired resonant frequency at which the system is excited;
- the computation of damping parameters from test measurements was made assuming that the studied system was linear. In practice majority of actual systems are non-linear;
- the modal interference in closely spaced modes was affecting the estimated damping factors.

Modal damping values for multiple degree of freedom (MDOF) systems could be estimated from the magnitude of the gain plot in the case of the magnification factor and bandwidth methods in two cases: the modal frequencies were not too closely spaced and the system was slightly damped. The central value for the resonant frequency interval and the value for the damping coefficient were given by the amplitude of the peak from gain diagram. The phase shift of 180((for second orders systems) would appear at a frequency in the vicinity of the central frequency determined from the gain diagram (in an interval including frequencies up to 10 times the frequency shown by the gain diagram).

Method	Measurements	Formulas
Logarithmic decrement method	A i – first significant amplitude A i+r – amplitude after r cycles	Logarithmic decrement
Step-response method	M p – peak value of response PO – percentage overshoot (over	

	steady-state value)	
Hysteresis loop method	(U – area of displacement-force hysteresis loop x 0 – maximum displacement of the hysteresis loop k – average slope of the hysteresis loop	Hysterectic damping constant Equivalent damping ratio
Magnification-factor method	Q – magnitude of FRF at resonance frequency	
Bandwidth method	((– bandwidth at 0.707 of resonant peak (r – resonant frequency	

Table 1. Classical damping measurement methods [4]

The above mentioned methods considered that the system has only one type of damping. The recent research efforts connected to the modal parameter estimation showed the existence of several forms of damping in MDOF systems. A considerable number of authors tried to determine an equivalent level of damping for the models. The use of equivalent damping for transient decay was not recommended because the equivalent viscous damping assumed a forced sinusoidal motion but some damping models depend on amplitude. Also the amplitude reduced simultaneously with the damping force in the system.

Ewins [5] emphasised the difficulties of extracting meaningful damping quantities from measured FRF data:

- associated with the measurement techniques themselves (damping effects are usually an order of magnitude smaller than the corresponding mass and stiffness effects);
- the underlying equations of motion are much more complex than it is considered;
- the features which influence damping – joint tightness, surface finish, temperature, wear etc. – are variable and apparently unrepeatable from day to day and system to system.

3. Continuous Wavelet Transform used for modal parameter identification of CNC machine tool feed drives

The analysis of non-stationary signals whose spectral character changes with time (such as vibration signals) calls for specific time-variant techniques which go beyond those employing the classical Fourier transform because when a signal is transformed into the frequency domain, time information is lost.

Wavelet transform (WT) represents a powerful tool for the analysis and synthesis of such signals offering simultaneous localisation of signal characteristics in spatial (or time) and frequency domains. The sharp transitions in the signal spectrum and the time of their occurrence are determined in the same time.

The wavelet analysis uses windows with variable size: long time intervals – when more low frequency information is required, shorter regions – when more high frequency information is wanted.

The WT was extensively used for identifying the modal parameters of civil engineering buildings (bridges, blocks). Only Luo et. al [6] used the wavelet analysis and global Fourier transforms for analysis and modelling of vibration signals from machine tools. A vibration model was developed considering the combination between continuous wavelet transform (CWT) and the discrete harmonic wavelet transform (DHWT) and the coefficients were identified with least-square algorithm.

Three techniques based on CWT were compared by Staszewski [7]: the WT cross-section procedure, the impulse response recovery procedure (based on wavelet domain filtering) and the wavelet ridge detection procedure. The advantage of WT over the classical complex envelope function consisted in decoupling the MDOF system into single modal components. The same author published a recent paper [8] where he tried to bring together some recent applications of wavelet analysis to non-linear systems from engineering. Besides the above mentioned methods, he discussed about cross-wavelet analysis, self-similar signals, coherent structures and chaos and the main conclusions were:

- Among the directions of recent research regarding the wavelet analysis used for the identification of non-linear systems are damping estimation and modal parameters estimation for MDOF systems with close modes;
- Higher levels of accuracy are reached due to wavelet analysis capability of representing solutions of partial differential equations at different scales;
- Wavelets could be used for finite element applications as shown by preliminary studies.

It was evident that previous modal parameter identification for CNC machine tools was not performed using WT (except Luo).

Pislaru [9] introduced a new procedure to extend the use of CWT to identify hybrid models of non-linear systems based on a frequency domain description to solve practical problems in the CNC machine tools field. The CWT applied to experimental signals was shown to be capable of detecting variations in the amplitude levels of weak components embedded in strong noise and non-stationary processes. Also the wavelet analysis was used to de-noise the signals without any appreciable degradation.

Pislaru et al [10] chose the Morlet wavelet as the mother wavelet because it gives the best compromise between frequency and time measurement. This mother wavelet is a function well localised in both time and frequency. This function is then dilated and translated to form a family of analysing functions. Table 2 shows that the WT converges in many function spaces where Fourier transform fails to do so.

Frequency from Bode diagrams [Hz]	Zeta for Bode diagrams	Frequency by CWT [Hz]	Zeta by CWT
35	0. 135	39	0. 097
74	0. 086	78	0. 126
112	0. 082	86	0. 174
119	0. 081	125	0. 052
131	0. 038		

Table 2. Identified values for resonant frequencies and damping ratios using Bode diagrams and wavelet analysis

The wavelet analysis was performed using the response of the system to random noise which do not generate any problems in the functioning of the machine. Meanwhile the Bode diagrams were plotted considering the swept sine input that had a great amount of energy for every frequency and was subjecting the CNC machine tool to strenuous effort. Besides this important advantage, the WT was able to uncover local and transient features of the signals and to identify the contribution of various modes at different times in the system response.

The resonant frequencies were manually determined from a 3-D diagram of CWT for the measured response of the feed drive. Pislaru et al [11] developed an algorithm for the automatic detection of the modal parameters through the removal of one resonant frequency at a time from the impulse response. The algorithm was applied for known simulated coupled modes.

The WT has become a valuable analysis tool due to its ability to elucidate simultaneously both spectral and temporal information within the signal. This overcomes the basic shortcoming of Fourier analysis (the Fourier spectrum contains only globally averaged information so the location of specific features in the signal are lost). The WT allows for the decomposition of the response signal while retaining temporal information.

More research has to be performed in order to apply the automatic detection of modal parameters from measured data that contains additive noise and non-linear aspects. This will represent an important contribution to condition monitoring applications where detecting on-line the parameters affecting machines dynamic performance is critical.

4. Methods used by modern experimental modal analysis

Experimental modal analysis is used to establish and verify mathematical models of structures and machines. The dynamic response of structures and the transmission of vibrations to the surroundings are critically determined by the damping mechanisms, and its value is very important for the design and analysis of vibrating structures. When the structure is modeled, the stiffness and mass distributions are quite well determined, but there is great uncertainty regarding the energy dissipating mechanism provided by the damping of the structure because it is the least well understood. The damping must be estimated by experimental modal analysis in order to validate these models.

Careful considerations are required for successful experimental modal analysis, starting from the data acquisition stage up to the modal parameter extraction. The required steps for a successful experimental modal analysis are:

- Preparation of the structure to prevent or minimise any external influence;
- Selection of the excitation system best suited to the structure;
- Measurement using Fast Fourier Transform (FFT) based spectrum analyser;
- Measured data post-processing to extract the modal parameters by a curve-fitting method.

The estimation of the modal parameters by the examinations of the measurement results could be done by using either manual or computer assisted methods.

Two fundamental methods of modal parameter extraction are available: *frequency* and *time domain* methods. The majority of modern modal parameter extraction studies employ the frequency domain method by examining the FRF data. The invention of modern dynamic signal analysers which can easily produce the frequency domain data and the advance of modal analysis software and computing technology are responsible for this trend.

The time domain methods investigating the IRF (Impulse Response Function) data are only utilised for a number of specialised applications (such as the modal analysis of structures with very low natural frequencies, transient, non-linear or frequency variant events). Lin et al [12] developed a derived equivalent eigensystem algorithm which has two main advantages in comparison to the existing identification methods in time domain:

1. the order of the measured data should not be determined prior to the identification process;
2. **the identification process becomes numerically more stable and the identified results become more accurate because the inverse of the system matrix is rank-deficient.**

Ewins [13] mentioned that the fundamentals of modal parameter extraction should include: checks of the FRF data validity, application of Mode Indicator Functions and SDOF and MDOF curve fitting methods.

The modal parameter estimation method in the frequency domain using the numerical technique involves two phases of analysis: suitable theoretical model synthesis and modal parameter extraction using a curve fitting technique. The order of the theoretical model is normally estimated to be at least the number of peaks observed in the measurements, whereas the curve-fitting algorithm can be selected from a number of available techniques (see Table 3).

Type of modal analysis	Techniques / methods
Single degree of freedom (SDOF)	Manual techniques Automated inverse FRF line fit method
MDOF	Non-linear least squares method Rational fractional polynomial method Lightly damped structures method
Global and poly-reference	Global rational fraction polynomial method Global singular value decomposition method

Table 3. Methods used for different types of modal analysis

Iglesias [14] studied the relation between the accuracy of estimated damping ratio and various modal parameter extraction techniques, truncation in the FRF, close modes, separated modes. Four methods were investigated: Prony or Complex Exponential Method (CEM), Ibrahim Time Domain (ITD) Method, the Rational Fraction Polynomial Method, and the Hilbert Envelope Method.

The Rational Fraction Polynomial Method proved to be the most reliable method in the frequency domain because the damping ratio estimation was not affected by the truncation in the FRF.

The FRF lost a lot of information when a single mode was isolated and the calculated IRF had leakage error when using the CEM and ITD methods as a single-mode methods.

The estimated damping ratio of the highest natural frequencies near to the maximum FRF frequency were not exact when the CEM or ITD method were used to process a truncated FRF. The heavily damped systems should be analysed by CEM and ITD methods.

5. Conclusions

The paper presents a critical appraisal of existing methods for the identification of modal parameters for CNC machine tool feed drives.

The classical methods for modal parameter identification are analysed and the shortcomings of the Fourier Transform are overcome by Wavelet Transform. The Continuous Wavelet Transform applied to the measured impulse response detects variations in the amplitude levels of weak components embedded in strong noise and non-stationary processes. Also the signals can be de-noised without any appreciable degradation.

An algorithm for the automatic detection of the modal parameters through the removal of one resonant frequency at a time from the simulated impulse response was developed. The next step will be to improve this algorithm in order to determine modal parameters for experimental data containing strong coupled modes, noise and non-linearities effects.

Several methods used by modern experimental modal analysis in time and frequency are analysed and their suitability for various applications is discussed.

An important conclusion is that the accuracy of estimating damping ratio can be affected depending of the method used and the characteristics of the FRF.

The evaluation and comparison of the existing methods for modal parameter identification helps the designers and industrial and academic researchers to find which one is the most reliable method with respect to certain characteristics of experimental data. In this way modal analysis extraction techniques could be developed ensuring more reliable identification of the modal parameters.

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References

[1] Gatzwiller K. B., *Introduction to Modal Analysis and Operating Deflection Shape*. B & K Course Notes BA 7069-12, Naerum, Denmark, January 1990.

[2] Ewins D. J., *Modal Testing of Rotating Machinery Structures*. Tutorial at the 5th International Conference on Rotor Dynamics, Darmstadt, 1998.

[3] Verboven P., Guillame P., Van Overmeire M., *Improved Modal Parameter Identification by Non-Parametric Modelling of the Measurement Noise.* Proceedings of the 17th International Modal Analysis Conference, Kissimmee, FL, 8-11 Feb 1999, vol. 3727, Ch. 313, pp. 1984-1990, 1999.

[4] De Silva C. W., *Vibration- Fundamentals and Practice.* CRC Press, London, 2000.

[5] Ewins D. J., *Basics and State-of-the-art of Modal Testing.* Sadhana, vol. 25, part 3, June 2000, pp. 207-220, 2000.

[6] Luo G. Y., Osypiw D., Irle M., *Vibration Modelling and Identification Using Fourier Transform, Wavelet Analysis and Least-Square Algorithm.* Proceedings of 2 nd International Symposium on Multi-Body Dynamics: Monitoring & Simulation Techniques. Bradford Univ., June 27-28, pp. 153- 167, 2000.

[7] Staszewski W. J. – *Identification of Damping in MDOF Systems Using Time-Scale Decomposition.* Journal of Sound and Vibration, vol. 203, part 2, pp. 283 –305, 1997.

[8] Staszewski W. J., *Analysis of Non-linear Systems Using Wavelets.* Proceedings of IMechE, Vol. 214, Part C, pp. 1339 – 1353, 2000.

[9] Pislaru, C., *Parameter Identification and Hybrid Mathematical Modelling Techniques Applied to Non-Linear*

Control Systems. Ph.D. Thesis, University of Huddersfield, U.K., 2001.

[10] *C. Pislaru*, J. M. Freeman, D. G. Ford – *Modal Parameter Identification for CNC Machine Tools Using Wavelet Transform.* International Journal of Machine Tools and Manufacture, vol. 43/10, pp. 987 – 993, 2003.

[11] C. Pislaru, D. G. Ford, J. M. Freeman, *Identification of Modal Parameters Affecting the Dynamic Performance of a CNC Machine Tool*. Proceedings of the 6th Internat. Conference on Laser Metrology and Machine Tool, CMM and Robot Performance (LAMDAMAP 2003), Huddersfield, UK, pp. 161-170, 2003.

[12] Lin, R. M., Lin, M. K., Wang, Z., *Structural Dynamics Identification Using Derived Equivalent Eigensystem Algorithm.* Proceedings of the 14th Australasian Conference on the Mechanics of Structures and Materials. University of Tasmania, Habort, pp. 615 – 619, 1995

[13] Ewins, D. J., Modal Testing, *Theory, Practice and Application*, 2nd Edition, Research Studies Press, Baldock, Hertfordshire, 2000.

[14] Iglesias, A. M., *Investigating Various Modal Analysis Extraction Techniques to Estimate Damping Ratio.* MSc Thesis, Virginia Polytechnic Institute, 2000.
