International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 7, Issue 6, June 2017)

Review on Determination of Forces using Inverse Techniques

Prof. Ratan A. Patil[1], Dr. S. L. Gombi[2]

[1]Jain College of Engineering, Belgaum Karnataka, India
[2]Gogte Institute of Technology, Belgaum Karnataka, India

***Abstract* — The variation in applied force when dealing with deformable bodies is one of the important factor to be taken into consideration. The body which is loaded statically deforms linearly elastic and the deformation is directly proportional to the applied force. But the same concept cannot be applied when the body is subjected to impulsive or sudden forces. In these cases direct measurement of forces are impossible, hence inverse methods are used to determine the forces from the measured responses of the body. This paper represents an overview of methods and inverse methods for indirect determination of force.**

***Keywords*—force identification, inverse methods, time and frequency domain, ill poised, condition number, frequency response function.**

I. INTRODUCTION

In designing reliable and cost effective designs, the analysis of structures or the engineering equipment, it is very much desirable to know at the particular design stage the locations and magnitudes of the external loads transmitted to the structure. These loads may be static or time varying dynamic loads. The stresses induced in the structure are a function of the applied loads. Knowledge of the loads early in the design process is vital for design optimization and effective analysis that ensures the structural integrity of the product. Accurate prediction of the loads leads to greater confidence in numerical simulation such as finite element analysis which, in turn, significantly reduces the reliance on expensive and time consuming experimental testing.

Identification of dynamic force excitation on a system is important for performance evaluation, design optimization, noise suppression, vibration control as well as condition monitoring. However, there are many situations where the direct measurement of the excitation forces is not possible or feasible. For example, engine torque pulses and shaking forces are difficult to measure since these forces are distributed throughout the engine. In such a case, direct measurement by using force transducer is not possible due to the difficulty of installation and dynamic characteristic altering problem. Therefore, force identification using the inverse method is used to solve the problem.

Impact force is the main cause for material fatigue of many structures especially in light weight structures, so it is useful to understand the characteristics of loading profile, such as impact location and its time history. At the development and modification stage of a lightweight structure design, better information about the loads experienced by the structure through the iteration process will assist the development resulting in a better design. Identification of the input forces and their locations is helpful to identify areas that are more susceptible to damage. The amplitude of force reflects the vibration condition of the structure so that any requirements for stiffening or structural modification can be identified to preserve a better structural integrity

When the structure is subject to an unknown force, knowledge of the mathematical model to represent the structure and the measured response due to the unknown force is essential so as to develop the force-prediction model for determining the force contents. In general, the force contents can be the magnitude, direction and location. The external forces can be categorized into various forms. One is the spatial-variant type such as point forces and distributed forces. Another is the time-variant type such as the impact, harmonic, periodic and random forces. The time history or the frequency spectra of the force may be of interest. The other is the spatial- and time-variant type such as moving forces.

II. DYNAMIC LOAD ESTIMATION TECHNIQUES

Dynamic load estimation techniques are applicable to the case where the forces to be estimated are dynamic in nature, i.e., they are a function of time. This area of research can be further sub-classified into— (i) time domain, (ii) frequency domain.

2.1 Time Domain Method

Time domain techniques are the most recent developments that aim towards estimating the input forces from measured response in time domain. The response of a structure as a function of its Impulse Response Function (IRF) and the forces acting on the structure is given by the convolution integral Eqn. (2.1) which is restated here for ease of reference.

IJETAE EXPLORING RESEARCH AND INNOVATIONS

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 7, Issue 6, June 2017)

$$X(t)= \int_0^t [h(t-\tau)]\{f(\tau)\}d\tau \quad (2.1)$$

The problem at hand is to solve this equation for unknown forces from the knowledge of the IRF and measured responses.

2.2 Frequency Domain Method

Frequency domain methods utilize a linear relationship between the applied forces and the measured response as a function of frequency. This linear relationship, also known as transfer function of the system, is called the frequency response function of the system. Consider the well-known convolution integral that computes system response from the input forces:

$$\{x(t)\}= \int_0^t [h(t-\tau)]\{f(\tau)\}d\tau \quad (2.1)$$

Where x (t) is the ($n_s \times 1$) response vector,
f (t) is the ($n_f \times 1$) excitation force vector,
h (t) is the ($n_s \times n_f$) Impulse Response Function (IRF) matrix.

Taking the Fourier transform of Eqn. (2.1), the relation can be expressed in the frequency domain as:

$$\{X(\omega)\} = [H(\omega)]\{F(\omega)\} \quad (2.2)$$

where ω is the circular frequency,
{X(ω)} is the ($n_s \times 1$) response vector,
[H (ω)] is the ($n_f \times 1$) excitation force vector,
{F (ω)} is the ($n_s \times n_f$) Frequency Response Function (FRF) matrix.

The FRF can be obtained from experimentally measured data, or can be reconstructed from a modal model of the system, or can be obtained from finite element method. It completely defines the dynamic characteristics of the system. {X (ω)} can be measured experimentally as any of the physical quantities—displacement, velocity, acceleration, or strain. The relationship between strain frequency response function and displacement frequency response function has been explored by several authors (Li et al., Tsang). Once {X (ω)} and [H (ω)] are known, the problem now remains that of solving for {F (ω)} and thereby computing the time history of the input forces f (t) using the inverse Fourier transform. For square $n_s = n_f$ and non-singular [H (ω)], Eqn. (2.2) can be inverted to give:

$$\{F(\omega)\} = [H(\omega)]^{-1}\{X(\omega)\} \quad (2.3)$$

Unfortunately, this inverse problem is not as easy and straightforward as the mathematics suggests.

Stevens (1987) presented an excellent overview of the difficulties posed by this class of inverse problems. Typically, FRF consists of a number of resonant peaks separated by anti-resonance valleys.

2.3 Impact force Identification

J. Wang, S.S.Law, Q.S.Yang [1] – They studied the accuracy and effectiveness of force identification in time domain which can be influenced by the conditioning of the structural system Markov parameter matrix(Mpm). The sensor placement methods based on the conditioning analysis of Mpm for improving the identification of input force were studied. One method is based on direct computation of the condition number of the matrix, and it would involve computation for many different combinations of sensor locations. The second approach is based on the correlation analysis of the system Mpm. The performances of these two methods are compared in numerical simulations with respect to their efficiency and accuracy. The performance of both methods is similar when the number of combination of sensors is small. But, when there are many combinations of sensor locations, the method based on correlation analysis of the Markov parameter matrix performs better.

Sung-Jong Kim and Sang-Kwon Lee [2] - They presented experimental results of source identification for a non-minimum phase system. They used a causal linear system which is described by matrix form. The inverse problem is considered by matrix inversion. Direct inverse method cannot be applied for a non-minimum phase system, because the system has ill-conditioning. SVD inverse technique is used to execute an effective inversion. In a non-minimum phase system the system matrix may be either singular or near-singular and has small singular values. These very small singular values have information about a phase of the system and ill-conditioning. Using this property solving the ill conditioned problem of the system and then verify it for the practical system (cantilever beam). The experimental results show that the SVD inverse technique works well for a non-minimum phase system.

Chih-Kao Ma, Chih-Chergn Ho [3]-Their study proposes an inverse method to identify input forces of non-linear structural systems. The method is an extension of the linear structural systems. The estimation is done using extended Kalman filter and a recursive least-squares estimator. By using the inverse method, input forces acting on non-linear structural systems are estimated from measured dynamic responses. In this work, numerical simulations of input forces estimation of non-linear lumped-mass systems are performed to verify the practicality and accuracy of the proposed algorithm.

Piotr Pawełko, et al [4] - They developed a method for estimation of cutting force model coefficients. The method makes use of regularized total least squares to identify the cutting forces from the measured acceleration signals and the frequency response function (FRF) matrix. A regularization method is developed which is based on the relationship between the harmonic components of the cutting forces. The method is compared with unregularized methods and common Tikhonov regularization combined with GCV and L-curve methods. The proposed method provides more accurate estimates of the cutting force coefficcients than the unregularized method and common regularization techniques.

Shrinivas L. Gombi and Dr. D. S. Ramakrishna [5, 6]- In this work effect of impact force on the cutting tool during machining is estimated. A preferred approach is addressed to this problem in determining the Frequency Response Function (FRF) matrix. The structural responses are measured and dynamic forces are calculated based on the Least Square Scheme. In this work acceleration response is used as input for force prediction. The impact force history prediction algorithm is developed in both time and frequency domains to determine the impact force amplitude. In time domain the accelerations due to impact load is first predicted. The sum of mean square errors problem is thereby constructed and is then solved for the amplitude of the impact force. The accelerance method is used in the frequency domain. Results show that the method outlined for the identification of the magnitude of the impact force, apart from being accurate and robust to the effects of measurement noise, may be extended to solve problems for more general nature.

Xingjun Wang, et al [7]- They proposed a simple, rapid, and low-powered impact estimation method based on energy flow direction estimation through a pair of piezoelectric sensors. The estimation energy flow is expressed by a Pointing vector subsequently linked to piezoelectric sensor voltage outputs. The proposed approach is verified by numerical simulations and experiments.

Bor- Tsuen Wang, Kuan- Yuan Lin [8] - In this paper the force prediction for cantilever beam subjected to harmonic excitation is presented. Assuming the structural parameters known, the acceleration response of the beam due to the harmonic excitation is measured and used as the input for the prediction model. Using the developed force prediction algorithm harmonic force amplitude and its location is determined simultaneously. The beam response excited by harmonic force is first derived. The optimization problem to determine the harmonic force amplitude and location is formulated. Theoretical simulations are the one to demonstrate the feasibility and correctness of the developed force prediction algorithm. The results of this experiment show that the harmonic force amplitude and its location can be reasonably predicted.

Tsung-Chien Chen [9]– They used innovative intelligent fuzzy weighted input estimation method to estimate the unknown time-varying input force .The algorithm includes the Kalman Filter and the recursive least square estimator which is weighted by the fuzzy weighting factor based on the fuzzy logic inference system. The work presents an efficient robust zone, which is capable of providing a reasonable compromise between the tracking capability and the flexibility against noises. The capability of this inverse method are demonstrated in the input force estimation cases of the plate structure system. The proposed algorithm is compared by alternating between the constant and adaptive weighting factors. The results show that this method has the properties of faster convergence in the initial response, better target tracking capability, and more effective noise and measurement bias reduction.

Min Wan, Wei Yin, et al [10]–They studied the cutting forces samples from machining processes which may be distorted by the dynamic response of measuring system. Traditional methods, whether discrete inverse filter or Kalman filter, may result in accuracy loss due to inaccurate approximation of transfer function. This paper proposes an improved inverse filter to achieve accurate and efficient correction of the distorted cutting forces. Spline curve-based interpolation scheme is proposed to approximate the transfer function of the measuring system. The transfer function corresponding to the frequencies of the measured cutting forces obtained by this method can be close to the actual response of the cutting system to the most degree. As a result, the corrected cutting forces can well reflect the actual physical response of the machining processes.

TadeuszUhl[11]-They studied the inverse problem and its application for damage detection, and assessment. The methods applied are based on vibration measurements & based on wave phenomena in structures. The damage in the structure is defined as improper operations or change of material properties. The methods are classified in two groups; one which is based on identification of structural properties or materials properties changes, & the second is based on loads identification. Load identification problem is based on structural response measurements &is directly inverse identification problem. But the problem of material properties changes and structural parameters changes is typical identification problem which is based on measured input and structural response parameters of models.

They studied the identification of contact forces between rail track and wheel of rail vehicle during operation based on bearing boxes acceleration measurements where numerical methods were formed & implemented.

S.Y. Khoo, Z. Ismail, et al [12] – They studied the effects of impact excitation force on the integrity of a light weight structure, where impact force identification is done. The methodology used was Operating Deflection Shape (ODS) analysis, Frequency Response Function (FRF) measurement and pseudo-inverse method to evaluate the dynamic forces. A rectangular plate with four ground supports was used as a test rig to simulate the motions of a simple vehicle body. By using the measured responses at remote points that are away from impact locations and measured FRFs of the test rig, unknown force locations and their time histories are measured. The performance in various cases such as under-determined, even-determined and over-determined cases was experimentally done. This force identification method was examined for different response combinations and various numbers of response locations. For the over-determined case, good combination of response and high number of response locations give the best accuracy of force identification result compared to under-determined and even-determined cases.

2.4 Impact force Reconstruction

A. N. Thite, D.J. Thompson [13]– The1forces measured by inverse technique method are prone to errors which arise due to a combination of errors in the measurements and high condition numbers in the matrix of transfer functions to be inverted.. When the condition numbers are small, the measurement errors simply propagate without much amplification. Due to modal behavior of the structure, the condition numbers can vary significantly over the frequency range and with the spatial location of the response measurements. The spatial variation can be quite considerable across the structure. They have worked on to reduce error magnification in inverse methods by an 'optimal' spatial distribution of response locations. They developed a method which is based on the minimization of the average condition number across the frequency range. For many possible locations the method can involve excessive calculation. An approximate method is proposed which results in consistently good location selection for use in inverse force determination but involves much less computational effort .

Fergyanto E. Gunawan [14] - They studied the Levenberg–Marquardt algorithm to solve the ill-posed impact-force reconstruction problem.

The problem is important as the impact-force particularly of the pulse-type are difficult to be measured directly. In this case, the necessity of regularization is enforced by means of the trust region approach. This study mainly contributes a systematic approach to locate the optimal solution by tracking the L–M parameter. The proposed method is evaluated by solving two typical problem existed in the inverse problem of the impact-force reconstruction. Reasonable accurate impact-forces were produced from the both evaluations.

Linjun Wangab, Xu Hana, et al. [15]- A regularization method is proposed and applied to the identification of multi-source dynamic loads acting on a surface of composite laminated cylindrical shell. The regularization is the approximation of an ill-posed problem by a family of neighboring well-posed problems. A numerical regularization technique is proposed based on the construction of a regularization operator. The method is applied to load identification of composite laminated cylindrical shell. The transient displacement response can be obtained by the FEM. The multi-source dynamic loads on a surface of composite laminated cylindrical shell are successfully identified, which demonstrates the efficiency and robustness of the method.

E. Jacquelin, A. Bennani, P. Hamelin [16] – They studied the deconvolution & the purpose to analyze a deconvolution technique to solve the problems which occur. The associated deconvolution problem depends on the location of the measurement points. The deconvolution problem is ill-posed problem & the results at times are unstable& hence necessary to regularize the problem, which consists of adding a condition to the solution which does not appear in the initial problem. They necessitate the determination of a parameter using SVD &the difficulty is to calculate an appropriate value of this regularization parameter. The methods are successfully used to recover an experimental force.

Yi Liu, W. Steve Shepard Jr. [17] – They studied the reconstruction of distributed forces. In traditional modal method of force reconstruction, the forcing spatial function is decomposed only over the known forcing region. Numerical simulations shows that when compared with traditional modal method, this new method tends to obtain better reconstruction results while requiring fewer basis functions. In the improved method for reconstructing spatially varying dynamic forces, the force and response are represented using tailored sets of basis functions. This approach, like other inverse methods, is also an ill-posed method.

To solve this, a regularization process is introduced to increase the inverse stability. Numerical results show when the regularization process is applied to simulated response measurements that include noise, the new method is able to reconstruct spatially distributed external forces with improved accuracy.

Uhl T., Mendrok K. [18] – They presented loading force identification technique. Load identification methods are based on the solution of the inverse identification problem. For both linear and nonlinear systems, methods based on the minimization of assumed objective functions have been formulated. The least square error between the simulated and measured system responses has been used as the objective function. The dynamic programming optimization method formulated by Bellman is used for the minimization of the objective function to estimate the excitation forces. The inverse identification problem is ill-posed because not all the state variables or initial conditions are known. Ill-posed inverse identification problems are solved using the generalized cross-validation method, the dynamic programming technique and Tikhonov's method. Numerical and experimental tests on a laboratory rig were made to verify the formulated procedures.

M. T. Martin and J. F. Doyle [19] - Inverse problem of solving the impact force history using experimentally measured structural responses that tends to be ill-conditioned is converted into a well-conditioned problem using frequency domain deconvolution method. This helps in clarifying fundamental difficulties and issues involved in this problem. In this paper force reconstruction obtained using experimentally measured acceleration responses from four example structures are used to illustrate the points.

III. CONCLUSION

The accuracy and performances of force identification in time domain based on state space is influenced by the ill-posedness of the problem and measurement noise, and a combination of which would lead to computation instability of the inverse problem. An improved condition of the inverse problem may help to improve the computation. The method based on direct computation of the condition number of the matrix. Sensor location combination corresponding to the minimum condition number can be considered as the optimal sensor placement. The study on the ill-posed impact-force reconstruction problems can be done, on the basis of the Levenberg–Marquardt iterative solution method, to find the optimal solution of the problem iteratively.

The method, unlike the SVD-based method, requires significantly less the computer memory; therefore, for a problem that cannot be solved by the SVD-based method due to limitation on the computer memory, the problem should be able to address using the levenberg Marquardt method.

A regularization method can efficiently and stably identify the multi-source dynamic loads acting on the structure by the noisy response. Additionally, in the numerical simulations, the regularization method can provide better approximation of true loads. The force reconstruction method can be used to determine spatially distributed dynamic forces from measured structural responses.

For non-linear structural systems the inverse method to estimate input forces consisting of: the extended Kalman filter and a recursive least-squares estimator can be used. Damage detection, localization and damage assessment problem can solved employing known techniques of inverse problem solution. But presence of uncertainties in both models and experimental data are strong limit in this application of inverse problem. The localization of forces corresponds to the transmissibility matrix having a minimum accumulated error along the frequency range.

The intelligent fuzzy weighted estimator is an efficient adaptive and robust inverse estimation method for the estimation of the unknown time-varying input with the unpredicted modeling and measurement errors, and the transient measurement bias due to the instrument.

REFERENCES

[1] J. Wang ,S.S.Lawb, Q.S.Yang, Sensor placement methods for an improved force identification in state space , Mechanical Systems and Signal Processing, 2013.

[2] Sung-Jong Kim and Sang-Kwon Lee, Experimental identification for inverse problem of a mechanical system with a non-minimum phase based on singular value decomposition, Journal of Mechanical Science and Technology ,2008, 1504 -1509.

[3] Chih-Kao Ma,,Chih-Chergn Ho, An inverse method for the estimation of input forces acting on non-linear structural systems, Journal of Sound and Vibration, 2004, 953–971.

[4] PiotrPawełko,BartoszPowałka, Stefan Berczynski, Estimation of cutting force model coefficients with regularized inverse problem, Advances in Manufacturing science and Technology, Vol. 37, 2013

[5] Dr. Shrinivas L Gombi, Dr. D S Ramakrishna, A Solution to the Inverse Problem of Impact Force Determination from Structural Responses, International Journal of Engineering and Innovative Technology Volume 1, 2012

[6] Shrinivas L. Gombi and Dr. D. S. Ramakrishna, Estimation of Impact effect on The Cutting Tool of a Shaper from Measurement of Responses during Machining, Journal for Manufacturing Science & Production. Volume 12, Issue 3-4, Dec 2012, pp.161–169.

[7] Xingjun WANG, Daniel GuyomaR, Kaori Yuse, MickaelLallart, Lionel Petit, Impact force detection using an energy flow estimator with piezoelectric sensors, Higher Education Press and Springer-Verlag Berlin Heidelberg 2010, pp194–203

[8] Bor-Tsuen Wang, Kuan-Yuan Lin, Prediction of Harmonic Force Acting on Cantilever Beam, Proceedings of the 22nd International Modal Conference, Dearborn, Michigan, Paper No. 64, Session 3. 2004

[9] Tsung-Chien Chen, Intelligent fuzzy weighted input estimation method for the input force on the plate structure, Structural Engineering and Mechanics, Vol. 34,2010, 1-14.

[10] Min Wan, Wei Yin, Wei-Hong Zhang, Hui Liu ,Improved inverse filter for the correction of distorted measured cutting ,International Journal of Mechanical Sciences,2016.

[11] Tadeusz Uhl, Inverse problem in structural damage identification, Computer Methods in Mechanics, Poland, 2011

[12] S.Y. Khoo , Z. Ismail , K.K. Kong , Z.C. Ong , S. Noroozi , W.T. Chong , A.G.A. Rahman Impact force identification with pseudo-inverse method on a lightweight structure for under-determined, even-determined and over-determined cases, International Journal of Impact Engineering,2013.

[13] A.N. Thite, D.J. Thompson, Selection of response measurement locations to improve inverse force determination, Applied Acoustics, 2006, 797–818.

[14] Fergyanto E. Gunawan, Levenberg–Marquardt iterative regularization for the pulse-type impact-force reconstruction, Journal of Sound and Vibration, 2012.

[15] LinjunWangab, Xu Hana, JieLiua, XiaoqiaoHec and Fen Huang, A new regularization method and application to dynamic load identification problems, Inverse Problems in Science and Engineering Vol. 19, September 2011.

[16] E. Jacquelin, A. Bennani, P. Hamelin, Force reconstruction- analysis and regularization of a deconvolution problem, Journal of Sound and Vibration ,2003,81–107.

[17] Yi Liu, W. Steve Shepard Jr., An improved method for the reconstruction of a distributed force acting on a vibrating structure, Journal of Sound and Vibration ,2006,369–387.

[18] UhlT.,Mendrok.K, "Inverse Identification Problems: Theory and Practical Applications." 2003, ITE Press, Krakow.

[19] M. T. Martin and J. F. Doyle, "Impact Force Identification from Wave Propagation Responses," Journal of Impact Engineering, Vol.18, No.1, 2003, pp.65-77

[20] Adams, R., & Doyle, J. (2002). Multiple Force Identification for Complex Structures. Experimental Mechanics, 42 (1), 25-36.

[21] Inoue, H., Harrigan, J. J., & Reid, S. R. 2001. Review of Inverse Analysis for Indirect Measurement of Impact Force. Applied Mechanics Reviews, 54 (6), 503-524.

[22] Boukria, Z., Perrotin, P., & Bennani, A. 2011. Experimental Impact Force Location and Identification Using Inverse Problems: Application for a Circular Plate. International Journal of Mechanics, 5 (1), 48-55.

[23] Edouard Riviere Lorphevre, Enrico Philippi, Pierre Dehombreux, Inverse methods for cutting forces parameters evaluation, International Journal of Engineering Mechanics, 2007, Vol.14 (5), pp.1-13