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Sparse regularization for force identification using dictionaries

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ABSTRACT

The classical function expansion method based on minimizing l_2-norm of the response residual employs various basis functions to represent the unknown force. Its difficulty lies in determining the optimum number of basis functions. Considering the sparsity of force in the time domain or in other basis space, we develop a general sparse regularization method based on minimizing l_1-norm of the coefficient vector of basis functions. The number of basis functions is adaptively determined by minimizing the number of nonzero components in the coefficient vector during the sparse regularization process. First, according to the profile of the unknown force, the dictionary composed of basis functions is determined. Second, a sparsity convex optimization model for force identification is constructed. Third, given the transfer function and the operational response, Sparse reconstruction by separable approximation (SpaRSA) is developed to solve the sparse regularization problem of force identification. Finally, experiments including identification of impact and harmonic forces are conducted on a cantilever thin plate structure to illustrate the effectiveness and applicability of SpaRSA. Besides the Dirac dictionary, other three sparse dictionaries including Db6 wavelets, Sym4 wavelets and cubic B-spline functions can also accurately identify both the single and double impact forces from highly noisy responses in a sparse representation frame. The discrete cosine functions can also successfully reconstruct the harmonic forces including the sinusoidal, square and triangular forces. Conversely, the traditional Tikhonov regularization method with the L-curve criterion fails to identify both the impact and harmonic forces in these cases.

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1. Introduction

Measuring the dynamic force acting on the mechanical structure is a critical aspect for a large number of industrial applications such as structural health monitoring (SHM) [1,2], vibration active control [3], vibration transfer path analysis [4], etc. For instance, it is highly desirable to quantify the impact event on a wind turbine blade or an aerofoil induced by ice, bird or debris before additional damage accumulates. However, in many situations, placing force transducer between the source and structure is difficult or even impossible to measure the dynamic force directly, because either the excitation location is not accessible due to geometric issues or potentially it induces changes to the overall dynamic characteristics of

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the structure. For this reason, it is essential to develop indirect force measurement methods. The determination of the dynamic force from measured structural responses (such as acceleration, velocity, displacement and strain) is referred as force identification, force reconstruction or force deconvolution. However, force identification remains a challenging inverse problem, where a small error in measured responses can lead to a large fluctuation in the desired solution. To overcome the ill-posedness, various regularization methods such as Tikhonov regularization, truncated singular value decomposition (TSVD) and the basis function expansion method have been widely used for force identification.

To overcome the instability of the frequency response function (FRF) matrix near structural resonances, Liu and Shepard Jr. [5] applied TSVD and Tikhonov regularization with the least squares (LS) scheme for force identification both analytically and numerically. Thite and Thompson [6,7] compared different regularization methods through both simulation and experiment on a flat rectangular plate in the frequency domain and concluded that compared with TSVD, Tikhonov regularization could give considerably improved results. However, the frequency-domain model requires the long stationary time to calculate the FRF matrix inverse at each frequency. Furthermore, it might not be feasible for transient phenomena like impact events [8]. Conversely, the time-domain method allows us to obtain the time-varying forces at each specific time-step. Jacquelin et al. [9] applied the generalized SVD, Tikhonov regularization and TSVD to recover the impact force from an impact hammer acting on Al-5054 aluminum plate in the time domain.

An alternative method for force identification, named the function expansion method that employs various basis functions (such as sines and cosines, spline functions, wavelets, etc.) to represent the unknown force has been developed, where the force is approximately the sum of a set of weighted basis functions. Therefore, the coefficients of basis functions are solved instead of the original force and thus the number of unknowns is significantly reduced. Doyle [10] proposed a wavelet deconvolution method for impact force identification and constructed a Gaussian function as the basis function, where the number of basis functions is much less than that of data points. Unfortunately, Doyle did not provide the procedure to determine the optimum number of basis functions. Providing that the unknown force is a distributed harmonic force, Liu and Shepard [11] used tailored sets of triangle functions to describe the distributed force acting on a simply supported beam numerically, in which the number of basis functions is chosen subjectively. Hu et al. [12] employed Chebyshev polynomials to identify the impact force acting on CFRP laminated plates and compared the identified forces to obtain a converged one where the number of Chebyshev polynomials is set to be from 20 to 40. However, the quantity method for determining the optimum number of Chebyshev polynomials was not provided. Yan and Zhou [13] used two 1/4 cycle-sine pulses to approximate the impact force acting on a stiffened composite structure numerically. The corresponding parameters are optimized by the genetic algorithm. Naturally, the generality of this method is poor, since it is limited to impact force identification.

Li et al. [14] proposed used db6 wavelets to represent the impact and sinusoidal forces, where the number of wavelets is qualitatively and quantitatively determined by selecting the decomposition level of wavelets. Gunawan et al. [15] employed cubic B-spline functions in a Newton form to reconstruct impact force numerically, in which the number of basis functions is determined by a two-step method. In the first step, the loading and unloading stages of impact force are split; in the second step, the loading stage is reconstructed and refined. Later, Qiao et al. [16] applied cubic B-spline scaling functions based on wavelet multi-resolution analysis to reconstruct impact and sinusoidal forces experimentally, where the number of basis function is quantitatively determined by the condition number of coefficient matrix. Qiao et al. [17] proposed a cubic B-spline collocation method for impact force identification, where the optimum number of basis functions is indirectly determined by a modified generalized cross validation (GCV) criterion. In [18], three basis function expansion methods including the TSVD-based, Chebyshev-based, discrete cosine transform-based methods were considered in impact force identification, where the modified GCV criterion are used to determine the number of basis functions. Experiments demonstrate that the discrete cosine transform-based solution has the best accuracy. Nevertheless, these previous basis function methods commonly meet dilemma in determining the optimum number of basis functions.

Essentially, the previous regularization methods solving force reconstruction problem belongs to the l_2-norm regularization frame. In many cases, one has reasons to expect that most elements in solution could be zero. For instance, the impact force is sufficiently sparse relative to its dimension in the whole measurement time. It implies that the desired solution of impact force identification should have few nonzero entries. In this paper, inspired by the inherent sparse property of the impact force, the idea of sparse representation is introduced to the field of force reconstruction. In recent years, sparsity constraints have emerged as a fundamental type of regularizer by l_1 penalty instead of l_2 penalty [19]. Different from the popular regularization methods such as Tikhonov regularization using l_2 penalty, the sparse regularization methods using l_1 penalty require that the solution should have minimum nonzero values. Therefore, l_1 regularization can yield a very sparse solution [20]. Conversely, the l_2 solution typically has all nonzero values. It is worth noting that other types of dynamic forces such as harmonic forces are often not sparse in the time domain. For instance, the harmonic force may be sufficiently sparse in the frequency domain. Fortunately, most signals can be transformed into a sparse basis space by a wavelet or Fourier transform, where the coefficients are inclined to sparsity. Under this circumstance, either the force itself is sparse or it has a sparse representation in a proper basis space.

Particularly, the concept of sparse representation has received a lot of interest in signal/image processing [21,22]. For instance, since most images have a sparse representation in the wavelet domain, the Haar wavelets have been applied in solving deblurring problem using sparse regularization methods [23]. But the sparsity idea using l_1-norm penalty is rarely introduced for solving the inverse problem of force identification. Now, we start to formulate the force identification problem as a sparse representation problem with dictionaries. Since forces are not generally sparse in the time domain, the

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