FINAL REPORT

APPLICATIONS OF FREQUENCY AND WAVENUMBER NONLINEAR DIGITAL SIGNAL PROCESSING TO NONLINEAR HYDRODYNAMICS RESEARCH

Contract N00167-88-K-0049

Office of Naval Research

Applied Hydrodynamics Research (AHR) Program

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Abstract

In this report, we summarize recent progress in applying higher-order statistical techniques (such as higher-order spectra) and associated nonlinear system identification techniques to nonlinear hydrodynamic phenomena. In particular, we estimate, given model-test data of wave excitation and vessel/structure response, either frequency-domain or time-domain Volterra kernels. Knowledge of the Volterra kernels is important because the nonlinear physics is imbedded in them. Also such experimental knowledge is necessary to compare with theory, and to quantify the nonlinear mechanisms whereby energy is extracted from the wave excitation and down-converted or up-converted in the response frequency spectrum. Of fundamental practical importance is the fact that the approach is valid for Gaussian as well as nonGaussian excitation.

INTRODUCTION

Volterra series representations of weakly nonlinear systems have been utilized in studies of both nonlinear hydrodynamics and nonlinear system identification [1]. In the Volterra approach, the linear and nonlinear features of the system are described by the so-called linear, quadratic, cubic, etc. Volterra kernels. In the time domain these kernels correspond to the linear, quadratic, cubic, etc., impulse responses of the system, whereas, in the frequency domain they correspond to the linear, quadratic, cubic, etc. transfer functions. Of particular practical importance is the fact that the linear and nonlinear physics of the physical system is imbedded in the kernels, thus their experimental determination is often of the utmost importance in nonlinear hydrodynamics in particular, and nonlinear system identification, in general. Furthermore, knowledge of the Volterra kernels is necessary to quantify and track the nonlinear energy transfer between various modes of the system. Lastly, we note that experimental knowledge of the Volterra kernels is necessary to bridge the gap between theory and experiment, since theoretical values of the kernels can, in principle, be determined from the equations of motion. Examples of theoretical estimates of Volterra kernels in nonlinear hydrodynamics include the quadratic frequency response functions calculated by Dalzell and Kim [2, 3].

In general, the experimental determination of the Volterra kernels describing a nonlinear hydrodynamical system (or any nonlinear physical system, for that matter) is a very difficult task. For this reason, many investigators, both inside and outside of hydrodynamics, assume the system excitation (for example, sea wave excitation) possesses Gaussian statistics. Usually, the Gaussian assumption is made because of the resulting mathematical simplification in determining the Volterra kernels, not because it is always a valid assumption. However, our most recent work demonstrates that assuming Gaussian excitation, when, in fact, it is not, can lead to improper estimates of the Volterra kernels, and incorrect determination of the nonlinear mechanisms whereby energy is transferred from one frequency band in the excitation to another frequency band in the response. This point is considered further in this report.

OBJECTIVES

It is the overall objective of this work to demonstrate the feasibility of applying recent advances in digital polyspectral analysis and nonlinear system identification to important problems in nonlinear hydrodynamic research, such as nonlinear ship motion. Particular emphasis is placed on the determination of linear and nonlinear transfer functions (i.e., the frequency domain Volterra kernels), quantification of nonlinear energy transfer mechanisms, and generalization (to higher-order) of the concept of coherence spectra to provide a systematic method with which to quantify the "goodness" of the Volterra model. Of particular importance, in terms of making this a practical and useful methodology, is our objective of relaxing the commonly-made Gaussian excitation assumption.

An additional objective involves the extension of bispectrum techniques to include wavenumber k, in addition to the more commonly utilized temporal frequency ω. This is in recognition of the importance wavenumber plays in nonlinear hydrodynamics and in nonlinear wave/mode interaction phenomena.

TECHNICAL APPROACH

As indicated by the contract title, the approach very much rests upon recent advances in the innovative processing of signals and data from nonlinear physical systems. Specifically, the PI, Co-PI and their colleagues have developed, over the past decade, a truly multidisciplinary approach, which involves the creative integration of key concepts from the following fields: nonlinear systems (particularly Volterra series representation), mathematical statistics (higher-order statistics, such as polyspectra), digital signal processing and digital filtering techniques, and the relevant physics of the situation being investigated. See references [4 - 6] and the references cited therein for an overview of this subject. Although we and others have made significant progress in developing the approach underlying this work, it should be emphasized that it too is evolving and must continue to evolve if indeed it is to play an important role in nonlinear hydrodynamics research. To illustrate the correctness, feasibility, and practicality of the approach, it is applied, whenever possible, to model-test data characterizing nonlinear hydrodynamic phenomena.

Data Sets: During the past year, we have had access to four sets of model-test data, two sets involving ship motion provided by David Taylor Research Center, and two sets, one illustrating the response of a moored barge and the other the response of a tension leg platform to random seas, provided by Shell Development Company. All these data sets suffer from a common deficiency in that the data records are just not long enough; i.e., there is not a sufficient amount of raw data to get good estimates of the higher-order statistical quantities (such as polyspectra) necessary to characterize the nonlinear response of vessels/structures to wave excitation. The tension leg platform data was the best in this respect, and it is for this reason that we have had to resort, in our publications, to using this data set to illustrate our progress in applying digital polyspectral analysis and nonlinear system identification techniques to nonlinear hydrodynamics.

Volterra Models: Detailed descriptions of second-order Volterra models and our approach to determining the Volterra kernels from model-test excitation-response data are provided in references [7, 10, 13]. Once one has the linear and quadratic kernels, one can then model the linear and nonlinear mechanisms whereby energy is extracted from the wave excitation to drive the ship/structure at the wave excitation frequency (linear response) and at other possible resonant frequencies that lie outside the wave frequency excitation band (nonlinear response) [11, 12]. Furthermore, in reference [8], we generalize the concept of coherency to enable one to quantify the "goodness" of the linear and quadratic Volterra kernel models. Furthermore, using coherency concepts, we can quantify, for each frequency band, whether the response is linear, quadratic, or a function of both.

Wavenumber Considerations: Our approach to incorporating wavenumber into nonlinear hydrodynamics considerations has, as indicated in the proposal which led to this contract, been based on a data set characterizing transition to turbulence in the wake of a flat plate. Ideally, to obtain wavenumber information, one should sample the fluctuating field at many points in space which are sufficiently close together to avoid spatial aliasing (i. e., to avoid violating the sampling theorem in space). Clearly, such an approach is not practical, because of the extreme complexity associated with handling the time series data from all the points, and because the presence of so many probes would clearly influence the phenomenon to be studied. In principle, one could use a nonperturbing technique, such as LDV. However, nonperturbing probes tend to be expensive and complex, and, thus, not suitable for sampling the fluctuation field at many spatial points.

To simplify matters, we have, and are continuing to examine the possibility of extracting the desired wavenumber information from just two spatial samples. For this approach to work, one must assume that the fluctuation field to be made up of a superposition of waves. This assumption has enabled us to estimate the classical "linear" power spectrum $S(k,\omega)$ [18, 19], which of course indicates how the energy of the fluctuation field is distributed over ω and k space. Thus our current approach is to make the "wave assumption" and to extend higher-order frequency domain concepts, such as the bicoherence spectrum, to the wavenumber domain.

TECHNICAL ACCOMPLISHMENTS

As previously indicated, the Volterra kernels describing the linear and nonlinear physics of a system may be given in either the time or frequency domain. We have worked in both domains, with emphasis on applying polyspectral techniques in the frequency domain.

Frequency Domain: Digital polyspectral analysis techniques were used to determine linear and quadratic transfer functions from model-test data characterizing random sea wave excitation and vessel/structure response. As was mentioned in the approach section, we made use of model-test data of a scaled (1:54) model of a prototype TLP anchored in 1500 feet of water. Although not ship motion data, we believe that this data set does enable us to demonstrate the practicality and feasibility of using nonlinear signal processing techniques to investigate and quantify nonlinear hydrodynamic phenomena. Of particular practical importance is the fact that the approach is valid for nonGaussian (as well as for the more commonly assumed Gaussian) sea wave excitation. We have shown, by way of example, the deleterious effects of experimentally determining the Volterra kernels assuming Gaussian seas, when, in fact, they are not. We have also demonstrated how our approach might be utilized to decompose the vessel/structure response into its linear and nonlinear components, and to track the nonlinear energy transfer that takes place between different frequency bands in the wave excitation and vessel/structure response. Specific details may be found in references [8, 11 - 16].

Furthermore, progress has been made in generalizing the classical linear concept of coherency to quadratic [8] and cubic systems. Higher-order coherency spectra are very powerful tools with which to quantify the "goodness" of the nonlinear Volterra model and, hence, the confidence that we can place in such models once they have been determined from experimental data. The concept of coherency can also be used to detect the presence of nonlinearities. For example, in a very preliminary study, we utilized the concept of cubic coherency to detect the presence of cubic phenomena in towing tank data provided by John O'Dea of DTRC. Cubic phenomena were suspected by John O'Dea and his colleagues, but could not be verified by classical linear spectral analysis techniques.

Finally, we mention our recently initiated exploratory study [16] to recover first- and second-order wave-force spectra from time series records of model-test wave-amplitude excitation and structure/vessel response. This is essentially a deconvolution problem.

Time Domain: As previously mentioned, time domain kernels physically correspond to the linear, quadratic, and cubic impulse responses of the nonlinear system. Digitally speaking, the various impulse responses correspond to the so-called filter coefficients of a hierarchy of linear, quadratic, cubic, etc., digital filters [20]. The key challenge is to determine the various Volterra kernels (represented by the filter coefficients) from time series records of the wave excitation and vessel/structure response. As in the frequency domain case, the determination of the filter coefficients is considerably simpler if Gaussian wave excitation may be assumed [20]. We have developed and tested an algorithm based on Least Mean Square (LMS) estimation to determine the linear and quadratic filter coefficients when the sea wave excitation is nonGaussian [9]. Also, an extended second-order (i.e., quadratic) digital filter was developed that appears to be particularly advantageous with respect to modeling low-frequency drift oscillation phenomena with remarkably few filter coefficients [9]. Finally, we note an initial study where we have exploited the availability of our second-order Volterra filter to incorporate it into a feedforward compensator scheme to stabilize moored vessels/structures subject to low-frequency drift oscillations [17]. Although the data set utilized to demonstrate the performance of the quadratic filters was model-test data for a moored barge, we are confident that the techniques can be extended to modeling and forecasting the linear and nonlinear motion of unmoored ships.

Wavenumber Considerations: For efficient energy transfer both the frequency and wavenumber of nonlinearly interacting waves or modes should satisfy both frequency and wavenumber selection rules of the following type: $\omega_i + \omega_j = \omega_m$ and $k_i + k_j = k_m$. The bispectrum only considers those frequency triads which satisfy the ω selection rule. Our initial work, which is yet unreported, has involved examining the role of wavenumber mismatch Δk ($\Delta k = k_i + k_j - k_m$) on three-wave interaction phenomena. We have introduced both a new way to estimate wavenumber mismatch, and a new type of spatial coherence function. This latter quantity is in some sense a measure of the spatial coherence of the bispectrum. Relatively high values of the spatial coherence imply high confidence in the estimated value of wavenumber mismatch Δk, whereas, low values of the spatial coherence imply low confidence in Δk. These results will be reported upon in the near future.

SIGNIFICANCE

The availability and intelligent utilization of both frequency-domain and time-domain state-of-the-art nonlinear system identification techniques will significantly enhance the engineering and scientific productivity, at relatively small incremental costs, of model tests designed to elucidate the linear and nonlinear response of vessels/structures to nonGaussian random seas [15]. Second, the use of these techniques will facilitate comparison of model-test results with theory and numerical studies and, thus, should lead to new physical insights, and ultimately better design tools.

The fact that our approach (both time and frequency domain) is valid for nonGaussian wave excitation is very important, since it allows one to analyze and interpret "real-world" data, which is usually not Gaussian, or at least not sufficiently Gaussian to utilize various simplifying assumptions. To emphasize the significance of this result, consider the following. It is well known that if we excite a nonlinear system with a Gaussian input, then the response is nonGaussian. In this case, departures from Gaussianity of the response can be used to identify the nonlinear system. Now consider a second case where the excitation of the nonlinear system is nonGaussian. The response will be nonGaussian. In this case, however, we must take into account the nonGaussianity of the input, before utilizing the nonGaussianity of the output to identify the nonlinear system. Conversely, assuming a

Gaussian input (when in fact, it is not) will lead to erroneous nonlinear system identification, since the resulting model will model not only the physics of the nonlinear system, but also the nonlinear phenomena that gave rise to the nonGaussian excitation. For example, in model tests nonGaussian wave excitation may result from nonlinear wave interactions or nonlinear effects in the wavemakers. The deleterious effects of assuming a Gaussian excitation, when in fact it is not, are described by way of an example in ref. [14].

In our work, we have taken great care to emphasize the physical significance of the various higher-order statistical quantities that are calculated. For example, we have stressed how they may allow one both to spectrally <u>and</u> temporally decompose the response into its linear <u>and</u> nonlinear components and to track the nonlinear flow of energy from various frequency bands in the sea wave excitation to other bands in the nonlinear response of the ship or structure [11,12].

The improved second-order Volterra filters, which are causal, appear to have excellent potential in "forecasting" nonlinear ship motion and perhaps leading to improved positioning or stabilizing systems [9,17].

Finally, it should be emphasized that the results of the work carried out under this contract are directly applicable to other technical/scientific areas such as nonlinear mechanisms underlying (1) transition to turbulence and (2) fluid-structure interactions.

FUTURE EFFORTS

Since the work carried out under contract No. N00167-88-K-0049 is being continued under Contract No. N00014-88-K-0638, we point out some of the issues that we will address in the future. Since it is our objective to develop higher-order polyspectral analysis and nonlinear system identification techniques to a point where they are truly useful tools in investigating nonlinear hydrodynamic phenomena, it is essential that we have access to appropriate model-test data. As mentioned in the APPROACH section, current model-test data, although adequate for linear studies, is quite limited with respect to nonlinear studies.

Now that we have made significant progress in Volterra nonlinear system identification, future work will focus on interpreting the information contained in the kernels in terms of nonlinear hydrodynamics. For example, we will continue our exploratory effort to recover first- and second-order wave-force spectra from time-series records of wave-amplitude excitation and response. Second, since the importance of the nonGaussian statistics of the sea wave excitation is established, we plan to investigate new methods of testing Gaussianity based on higher-order spectral moments. Third, in both theory and experiment, Volterra kernels have, in the past, been often estimated using deterministic regular waves (linear case) or pairs of regular waves (quadratic case). Careful consideration needs to be given to any possible limitations in applying these kernels to field conditions where the wave-amplitude excitation is most appropriately modeled as a random process. Fourth, we would propose to develop guidelines for future model-tests that would insure that the significant investment in such tests would pay off in terms of new physical insight into nonlinear hydrodynamic phenomena.

We also are currently refining our newly developed statistical approach to measure wavenumber mismatch Δk and spatial coherence in studies of nonlinear wave interactions and the associated energy transfer.

PRESENTATIONS/PUBLICATIONS

Specific quantitative details of the progress described in this report may be found by consulting the references, particularly those denoted with an asterisk. Since this the first full year reported upon for the above contracts, the publications are in the form of conference proceedings. As the work carried out under the continuing contract matures, technical results will be written up and submitted for publication in refereed archival technical journals. Publications and presentations acknowledging support, or partial support, of the Applied Hydrodynamics Program of ONR are denoted with an asterisk. Such references are also annotated.

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11. * S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer and J. Y. Hong, "Spectral Decomposition of Nonlinear TLP Sway Response to NonGaussian Irregular Seas," Paper OTC 6134 Proceedings of the 21st Annual Offshore Technology Conference, Houston, Texas, May 1-4, 1989, 123-128. The thrust of this paper was to demonstrate that the second-order Volterra approach developed in previous references allows one to decompose, both spectrally and temporally, the response into its linear and quadratically nonlinear components.

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14. * S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Application of Recent Advances in Digital Nonlinear Time Series Analysis Techniques to TLP Model Test Data," presented at the International Symposium on Offshore Engineering - BRASIL OFFSHORE '89, Rio de Janeiro, August 21-25, 1989. Paper to appear in the proceedings, which is scheduled to be published by Pentech Press. E. J. Powers was on the organizing committee of this conference. In this paper, we point out, by way of example, the negative consequences of assuming Gaussian seas when, in fact, they are not.

15. * E. J. Powers, S. B. Kim, R. W. Miksad, F. J. Fischer, and J. Y. Hong "Analysis and Interpretation of TLP Model-Test Data Using Advanced Nonlinear Signal Analysis Techniques," to appear in the Proceedings of the Deep Offshore Technology International Conference and Exhibition, Marbella, Spain, October 16-18, 1989. The primary objective of this paper is to call attention to the fact that powerful digital data analysis tools exist and that they can considerably enhance the scientific and engineering productivity, at relatively small incremental costs, of model tests carried out to investigate linear and nonlinear hydrodynamic phenomena.

16. * S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Spectral Estimation of Second-Order Wave Forces on a TLP Subject to NonGaussian Irregular Seas," to be presented at and published in the Proceedings of the 9th International Conference on Offshore Mechanics and Arctic Engineering, Houston, Texas, Feb. 18-23, 1990. This paper presents the initial results of an exploratory effort to recover first- and second-order wave force spectra from model-test time series records of wave-amplitude excitation and surge response.

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