FINAL REPORT

Applications of Frequency and Wavenumber Nonlinear Digital Signal Processing to Nonlinear Hydrodynamics Research

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OBJECTIVES

Volterra series representations of weakly nonlinear systems have been utilized in studies of both nonlinear hydrodynamics and nonlinear system identification. 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.

It is the overall objective of this contract to investigate and demonstrate the feasibility of applying recent advances in nonlinear digital signal processing to nonlinear hydrodynamics, with special emphasis on the proper determination of frequency domain or time domain Volterra kernels representing nonlinear hydrodynamic phenomena. Proper determination of the Volterra kernels is a necessary step in developing models of nonlinear hydrodynamic phenomena, such as nonlinear ship motion in nonGaussian seas. Furthermore, the proper determination of the Volterra kernels is absolutely essential if the resulting models are to be used to "predict" the *nonlinear* response of ships to random seas.

Experimental determination of Volterra kernels over a higher-order multidimensional time or frequency space is a very complex task, particularly when the excitation is random. This has lead to many approximations, perhaps the most common of which is that the random excitation is assumed to be Gaussian. This assumption is made, not because it is always a good assumption, but rather because it leads to tremendous mathematical simplification in both the theoretical and experimental determination of Volterra kernels. However, recent work by the PI's has demonstrated that irregular wave excitation in ship towing tank studies may not be sufficiently Gaussian to justify using the Gaussian excitation assumption for modeling the nonlinear relationship between random sea wave excitation and the ship response, even though the assumption may be sufficient for studying linear characteristics. To put it another way, if one assumes Gaussian wave excitation when in fact it is not, then one effectively lumps the nonlinearities associated with nonGaussian seas in with the nonlinear physics governing the wave-vessel interaction. This will lead to erroneous models which will, in turn, lead to erroneous predictions of nonlinear ship motion in random seas. For this reason, an important objective of our work has been to take into account nonGaussian features of random wave excitation used in towing tanks, in order to differentiate nonlinear phenomena associated with the wave excitation from that associated with the wave-structure interaction.

Further objectives of the work deal with quantifying the nonlinear transfer of energy, whereby energy is extracted from various frequencies in the sea wave spectrum to reappear in other frequency bands in the ship response. This tracking of nonlinear energy transfer is considerably more complex in the nonGaussian case as will be commented on later. Other objectives include the generalization (to higher-order) of the concept of coherence spectra to provide a systematic way to quantify the goodness of the Volterra model, and extending Volterra kernel estimation procedures to third-order, i.e; cubically nonlinear systems. The necessity to develop third-order capability was provided by our recent and ongoing studies of nonlinear vertical-plane ship motion in random seas. The latter studies are being conducted in collaboration with John O'Dea of David Taylor Model Basin.

APPROACH

Our overall approach in developing and applying new nonlinear digital signal processing techniques to nonlinear hydrodynamic research rests upon the intelligent use of higher-order statistical concepts such as higher-order spectra and higher-order correlation functions to estimate, from experimental data, the frequency and time domain Volterra kernels, respectively. It should be emphasized that applications of such higher-order statistical concepts to nonlinear phenomena is a state-of-the-art research topic in its own right. Of particular practical importance is the fact that our approach is valid for random nonGaussian sea wave excitation, a fact that allows us to determine "correct" Volterra models for the nonlinear wave-vessel interaction. In other words, the resulting model is not contaminated by any nonlinear physics associated with the wave excitation itself. The fact that the PI, Co-PI and their students have been active in this latter field insures the rapid transfer of this new knowledge to the area of applied hydrodynamics research in general, and nonlinear ship motion in particular.

In summary, the approach is a mutidisciplinary approach based on intelligently integrating appropriate knowledge from the fields of nonlinear hydrodynamics, higher-order statistical analysis, nonlinear system identification, and digital signal processing. To illustrate the correctness, feasibility, and practicality of the approach, it is applied to experimental data. Specifically, we have focused on vertical motion of an S175 hull in random seas. The tests were carried out by John O'Dea and John Zseleczky at the United States Naval Academy towing tank.

ACCOMPLISHMENTS

Frequency Domain Analysis

Throughout the duration of this contract we have demonstrated the efficacy and practicality of utilizing advanced higher-order statistical analysis techniques to determine Volterra kernels that, in turn, may be utilized to model and ultimately predict the linear and nonlinear response of ships to random seas. In addition, we have illustrated that one can test the "goodness" of these models by generalizing the concept of linear coherency to include higher-order nonlinearities. In addition, the generalized concept of coherency enables us to test model basin and towing tank data for evidence of nonlinearities and to quantify the nonlinearities (e.g., quadratic vs cubic) as a function of frequency.

A very important consequence of wave-structure interactions is the fact that energy may be extracted from the sea wave spectrum and nonlinearly "upconverted" or "downconverted" to reappear at higher or lower frequencies, respectively, in the structure's response. This is especially deleterious when one of the "higher" or "lower" frequencies corresponds to a resonance of the structure. Quite recently, we have developed a very powerful methodology which allows one to track in detail this nonlinear flow of energy from the excitation wave spectrum to each and every frequency in the response. Such a capability could prove to be very powerful, for example, in investigating both sum and difference frequency excitation (in both quadratic and cubic cases), and in quantifying wave-structure interactions in general.

In tracking the nonlinear flow of energy, we must take the output of the linear, quadratic, and cubic components of the Volterra model, add them together, square the result, and then average. The power spectrum of the ship response at each frequency thus includes contributions corresponding the square of the linearic, quadratic, and cubic filter outputs taken individually. In addition, there are cross-product or "interference" terms corresponding to cross-products between the linear-quadratic, linear-cubic, and quadratic-cubic outputs. These interference contributions to the response power spectrum at each frequency can be negative or positive, depending on the relative phases of the two interfering outputs. When negative, such interference can considerably hinder the physical interpretation of the nonlinear energy transfer described in the previous paragraph. If the random sea excitation is Gaussian then one can eliminate the presence of the interference terms by use of an orthogonal model. However, in the more realistic situation of nonGaussian excitation one must contend with the interference terms. For this reason we have very recently considered, under sponsorship of ONR Grant No N00014-92-J-1046, new Volterra modeling methodologies which remain valid for nonGaussian sea wave excitation, but do away with the presence of the "interference" terms. These new modeling approaches also offer the advantage of reducing the complexity of the mathematics and enhancing the physical interpretation of the model in terms of the relevant nonlinear physics. These new results will be presented at the Nineteenth Symposium on Naval Hydrodynamics, Seoul, Korea, August 1992.

During this contract we have analyzed data corresponding to vertical plane ship motion. Specifically we were provided data by DTRC for the response of a standard ITTC S175 hull in both regular and random seas. We utilized recently developed (under another contract) cubic system identification techniques to quantify the degree of linearity and nonlinearity of the vessel response. Specifically, we utilized a generalized concept of coherency to quantify, at each frequency in the response, the percentage of "power" (as in power spectrum) that could be accounted for by the model. For regular wave excitation, we found for both pitch and bow acceleration that a linear model could only account for approximately 70% of the observed response at the dominant frequency. When a linear plus cubic model was considered, we found that this model accounted for close to 100% of the observed response. Furthermore, the analysis indicates that the additional 30% of the response is due to cubic interactions, where a triplet of frequencies (f_1, f_2, f_3) in the wave excitation mix to contribute to the response at $f_r = f_1 + f_2 + f_3$. Of particular relevance to this case are so-called degenerate interactions whereby a cubic system is excited at fo and responds at f_o ($f_o + f_o - f_o = f_o$). With respect to random wave excitation cubic effects appear to be present, but not as strongly present as in the regular wave data. By this we mean, the linear model typically accounts for 85% of the observed response and the cubic portion of the model accounts for 15%, or so. Negative interference effects between the linear and cubic components of the model are also apparent. In fact, it was the appearance of the negative interference terms in this data set that motivated us to consider alternative approaches to Volterra modeling (as described in the previous paragraph) that eliminate the presence of such terms. The towing tank data also illustrate how the usual assumption of linearity of the response can lead to incorrect predictions, as can the usual assumption of Gaussian random waves when, in fact, they are nonGaussian.

In estimating Volterra kernels from wave-excitation ship-response data the question arises as whether the techniques utilized in this contract do indeed yield the correct kernels. In the case of quadratic nonlinearities, the second-order frequency domain kernel is known as the quadratic frequency response function (QFRF). During this contract we reported on an investigation to compare the statistically estimated QFRF (using higher-order spectra techniques) with an analytically determined QFRF by Kim and Boo. These latter two investigators analytically determined the QFRF of a 500 ft. ship in 60 degree quartering random seas of a significant wave height of 18 feet. To obtain the time series for the resultant drift force, the QFRF is inversed Fourier transformed to get the quadratic impulse response function (QIRF) and then convolved with the excitation pseudo-random wave which has a Pierson-Moskowitz power spectrum. The resulting convolution provides the drift force time series. We were provided the wave-excitation and drift-force time series data and proceeded to estimate the QFRF and found it to be in excellent agreement with the theoretical QFRF. Furthermore the estimated QFRF is able to "predict" the simulated drift force within 1% mean square error.

Time Domain Analysis

Modeling and forecasting of the motion of a vessel subjected to random waves have been studied recently using nonlinear digital filtering techniques. Also, the capability of predicting the future nonlinear response of the vessel with relatively high accuracy has opened up the possibility of stabilizing a nonlinear vessel using feedforward as well as the more conventional feedback technques. We have developed a stabilization scheme which can considerably reduce the influence of random wave excitation on the sway motion of a moored vessel in an incident random wave field using a quadratically nonlinear digital filter and feedforward compensator, while at the same time guaranteeing stability using a classical digital PID controller. The proposed computerized stabilization scheme can be thought of as consisting of two parts: (1) a feedforward compensator which estimates the influence of sea wave on the vessel using a digital quadratic filter, and which generates a control signal that will counteract the predicted response of the vessel to the sea wave, (2) a feedback controller (digital PID controller) which reduces the sensitivity of a vessel to environmental forces and guarantees stability of the system.

Another important aspect of our time domain work involves the extension of adaptive filtering techniques to nonlinear Volterra adaptive filters. In this case, recursive algorithms are used to update the Volterra digital filter coefficients (i.e., the time-domain Volterra kernels). Thus, the time domain Volterra model is "self-learning" and can adapt or update itself to changes in sea-state or changes in the ship's parameters (due to battle damage, for example). We have extended the recursive algorithms to second-order Volterra filters and have focused on the following issues relating to fast algorithms (necessary for real-time operation); speed, convergence, and stability. Since the towing tank data for the S175 hull exhibits significant cubic effects in the vertical plane, we have, under the partial sponsorship of ONR Grant N00014-92-J-1046, recently initiated work to extend these concepts to third-order (i.e., cubically nonlinear systems).

Wavenumber Mismatch

Under this contract we have also studied nonlinear interactions in both frequency and wavenumber space. Digitally implemented bispectral and trispectral analysis techniques allow one to detect and quantify quadratic and cubic interactions in the frequency domain. Under this contract we have also investigated the role of wavenumber mismatch on such interactions. Specifically, we have developed new approaches to quantify both the wavenumber mismatch and the "goodness" of the estimated mismatch.

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 and towing tank tests designed to elucidate the linear and nonlinear response of vessels/structures to nonGaussian random seas. 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. It should also be emphasized that the algorithms and procedures developed under this contract can be used to analyze and interpret time-series data from numerical experiments as well.

It must be emphasized that in carrying out the work sponsored by this contract, we are endeavoring to develop practical engineering tools. For example, 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 sufficiently Gaussian to utilize various simplifying assumptions. Furthermore, we have investigated various algorithms to determine both time and frequency domain Volterra kernels because various practical applications may dictate one approach over the other.

FUTURE WORK

Future work will be devoted along the following two lines: (1) improving our ability to determine better nonlinear seakeeping models from experimental time series data and (2) testing and demonstrating the efficacy of the approach in collaboration with John O'Dea and utilizing towing tank data provided by him. This dual approach will enable us to test the predictive capabilities of the Volterra model for various random seas, compare models derived from regular and random sea excitation, test various modeling approaches designed to reduce the complexity and raw data requirements associated with cubic models, examine the robustness and uniqueness of the Volterra models, and investigate the feasibility of developing a probabilistic description of nonlinear responses based upon knowledge of the appropriate Volterra kernels.

PUBLICATIONS

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