REDUCTION OF SEAKEEPING DATA
AT THE DAVID TAYLOR MODEL BASIN

by

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HYDROMECHANICS LABORATORY

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ABSTRACT

Seakeeping data-reduction methods at the David Taylor Model Basin are reviewed. The method of autocovariance-transform digital analysis is shown to be deficient for some problems. The filter-square analog method employed by the SEADAC (Seakeeping Data Analysis Center) is shown to be more generally applicable to all data-handling problems. Proposed extensions of the SEADAC to include cross-spectrum analysis and to provide greater efficiency are discussed.

INTRODUCTION

The collection and analysis of seakeeping data has long been an important activity at the David Taylor Model Basin. Data collected in the model tanks have, until recently, offered no serious analysis problems, since the generated waves were sinusoids of constant amplitude and the responses of the model were essentially of the same nature. Interpretation of such data usually involved some frequency response function for particular speeds and heading (head or following seas) for each seakeeping event being studied. However, full-scale trials are another matter. Ship motions measured at sea are naturally complex functions of time which were originally treated in the most elementary statistical way. That is, maximum values and certain averages were computed for each seakeeping record.

With the introduction of the probabilistic solution to ship motions problems, a new tool, the energy spectrum, was offered to the naval architect as a means of describing some of the physical processes which contrive to make a ship sea-kindly, or not. The wealth of information
available through this new expression of seakeeping events was not delivered
without cost. In order to extract the much desired information from the
ship motions records, access to reasonably high-speed computers or special
electronic equipment was (and is) required. Although the cost of collect-
ing the raw data is high, the knowledge to be gained justifies the expense
of data reduction. Shortly after the concept of the energy spectrum appeared
in the literature, the age of the one-man desk-computer technique of sea-
keeping analysis passed into history.

At present, many laboratories are engaged in seakeeping investigations;
there is, however, no universal technique for data handling. Analysis
methods must be tailored to the needs of the individual laboratory, where
the scope of data collection, cost, and available facilities all play
important roles in selecting an optimum seakeeping analysis system.

The intent of this paper is to review the data-reduction methods
used at the Taylor Model Basin in the past few years, with emphasis on
current aspects and future plans. The present system of data handling
is the result of several years of studying analysis concepts and searching
for existing systems. It is by no means the best possible system (modifi-
cations are already being made), but it may serve as a guide to individual
thinking on particular data-handling problems at other laboratories.

GENERAL REMARKS ON DATA PROCESSING

A few preliminary remarks on data processing associated with energy-
spectrum computations will orient the reader to the material which follows.

There are two well-known methods for energy-spectrum computation; for
brevity's sake, they will be referred to as:

1 Autocovariance-transform method, and
2. Filter-square method.

There are also two ways of applying each method:

1. Digital computers, and
2. Electronic analog computers.

Finally, the computers may be either:

1. General purpose, or
2. Special purpose.

Each of the two methods may be treated by either analog or digital means and by general- or special-purpose computers. In principle, eight ways are available for calculating the energy spectrum of a seakeeping event; in fact, some of the ways are eliminated for various reasons.

A special-purpose digital computer for energy-spectrum analysis is yet to be designed. Since the general-purpose digital computer can handle the problem with ease, it is probable that a special-purpose digital computer will not be built unless special considerations, not now obvious, become important. This eliminates two of the eight ways of handling data. However, special-purpose analog computers are easily built (and even commercially available), so that general-purpose analog computers have seldom, if ever, been used for energy-spectrum analysis. This eliminates two more ways. The remaining four ways have been tried (in other laboratories) in the various combinations, and the result is two particular techniques which are now enjoying great popularity. They are: the autocovariance-transform-digital (general purpose) and the filter-square-analog (special purpose). The Taylor Model Basin uses both of these methods, and they will be discussed in connection with the type of data analysis system that each has generated.
THE AUTOCOVARIANCE-TRANSFORM DIGITAL METHOD

The principles of the TMB data-reduction system which involve the autocovariance-transform-digital method can be seen in the simplified block diagram, Figure 1. The information collected by the transducer is recorded on chart paper, as a variable time function. In the laboratory it is necessary to prepare this data for input to the UNIVAC or IBM 704 by reading the records at equally spaced intervals. Originally, the reading was done manually. There are approximately 1000 points per record, and if there is an average of 5 records per run and 10 runs per cruise, some 50,000 points must be read for each ship tested. As full-scale ship testing became routine, it was obvious that this method was unsatisfactory, both from the cost and accuracy point of view, and semiautomatic point reading was instituted. The data are now obtained directly on punch cards through manual positioning of a cross hair on the screen of a data-reader which magnifies the record. When the points are read manually, they are retyped on a punched tape; when they are obtained on punch cards, they are fed to a card-to-tape converter. In either case, the tape is the input to the digital computer, which calculates estimates of the spectral density (via autocovariance-Fourier transform) at discrete frequencies, and presents the results in the form of a list of numbers, each of which is proportional to the appropriate spectral density.

The output data is returned to the project manager, who converts the numbers to a graph (after correcting for calibration, scaling, etc.) which is the energy spectrum of the record that was analyzed. From the energy spectrum, various statistics are computed which describe the
particular seakeeping event being studied.

In spite of the great savings in labor derived from the high-speed computer, there is still too much effort and time involved in the preparation of data for input to the computer. In addition, recent trends at the Model Basin in intensive surveys of ship behavior and the resultant huge volumes of data have made the semiautomatic point-reading technique virtually obsolete. Furthermore, anticipated daily model testing, in irregular waves, in the almost completed TMB seakeeping facility, make such methods virtually impossible for future routine use. Also, in the use of the general-purpose digital computers there is the problem of remoteness of the project engineer from the analysis system. This problem is particularly evident in model testing where the results must be immediately available so that they may be used to modify the test program. Also, it is often useful to change the computational parameters during an analysis so that attention may be focused on one portion of the spectrum, where high resolution may be desired (slamming studies, for instance).

All this points up the benefits of the special-purpose computer which has the following advantages:

1. Permits monitoring of all analysis results by the project engineer.
2. Permits easy change of computational program, even during an analysis.
3. Assists in modifying model test program.
4. May be used aboard ship.

Since the electronic-analog filter-square method has become associated
with the special-purpose computer, several years have been spent in the study and assembly of such a system, and the result is the TMB SEADAC (Seakeeping Data Analysis Center) which has been recently inaugurated and is now in daily routine operation.

THE FILTER-SQUARE ANALOG METHOD

The basic functions of the SEADAC, as a data handler, may be summarized as follows:

1. Preparation;
2. Analysis;
3. Storage.

Even though the principle of filter-square is related directly to only the analysis aspect of the system, it has in fact dictated almost all of the design of the SEADAC.

To get a clear general picture of the operation of the system, see Figure 2.

The raw data, from as many as 14 transducers (T), is transmitted simultaneously to a magnetic-tape reel recorder in the field. This data is usually recorded at 1-7/8 ips and is sped up 512 times in the laboratory by a system of playback and re-record involving a reel recorder and a loop recorder. This is necessary because the filter system, which is the analyzer portion of the SEADAC, can most conveniently accommodate frequencies much higher than those obtained from seakeeping records; the speedup procedure effectively multiplies the original frequencies by 512.

During the speedup process, the information on the magnetic tape is recorded on chart paper, on a condensed scale, and put into a "book" which is a detailed account of the trial. The book is useful
to the project manager as a visual aid for the validity of the signal on the tape and as a check on the order of magnitude of the results obtained from the spectrum analysis. Figure 3 shows a page from such a book. The SEADAC contains two analyzers, two analog computers, and two X-Y plotters, all of available commercial design.* For the sake of discussion, only one spectrum analyzer system will be considered.

Each run is spliced into a loop and played into the analyzer system. One of the 14 channels of information is selected for analysis, and the signal contained thereon amplitude-modulates the carrier signal generated by a local oscillator. The decomposition of the seakeeping record into its spectral components depends on the concept of amplitude modulation, and although this is well known to those in the electronic field a brief description of this process, as it applies to the SEADAC, is given in the appendix.

The result of modulation is a signal composed of the carrier wave and two other components whose frequencies are the sum and difference of the frequencies of the carrier wave and the modulating wave. The component containing the difference frequency has an amplitude proportional to the amplitude of the modulating signal. A filter centered at a constant frequency, always less than or equal to the variable carrier frequency, will pass only those components which have a difference frequency equal to the pass-band frequencies of the filter (see appendix).

The end result of modulation and filtering is identification of the frequency being analyzed (from the oscillator readout panel) and a measure of the amplitude (from the modulated signal). The amplitude measure is next fed to an analog computer which squares the voltage

(representing the amplitude), and the result is plotted on the X-Y recorder. This process is repeated for all the frequencies in the seakeeping record as prescribed continuously by the oscillator. The output of the SEADAC is a continuous graph of averaged spectral density versus frequency. Figure 4 shows a selection of seakeeping spectra made by the SEADAC. Digital spectra of the same data made by the autocovariance-Fourier transform method are superimposed for comparison purposes.

The shapes are in good agreement. Where the fit is not perfect, one may look to the calibrations which control the ordinate scale of the spectrum. This factor is very sensitive and illustrates the necessity for frequent and careful calibration of equipment during data collection.

The width of the filter determines the resolution of the spectrum. There are 4 filters in the SEADAC: 2, 5, 10, and 20–cps. Figure 5 shows the results of analyzing a pitch record with three different filters. The ordinate scale is determined by the width of the filter. That is, the analysis for the 10-cps filter will be twice as high as the analysis for the 5-cps filter, etc. If each spectrum is divided by its particular filter bandwidth, a common ordinate scale results and the three spectra in Figure 5 will be superimposed.

In addition to computation of the spectral (energy) density, the analog computer can calculate the total energy in the spectrum (that is, the area under the curve) by integration. This is shown in Figure 6, where the integrated spectrum of a pitch record is superimposed on the energy spectrum of the same record. It is also possible to plot the amplitude of the filtered frequencies directly.
After each run is analyzed, the loop is stored in a labeled plastic container. When the analysis of all the data is completed, the book and all the plastic containers are filed for future reference. The tapes will always be accessible through the book.

The general scope of this paper forbids a detailed account of the flexibility and many subtleties of the SEADAC. For a complete and detailed account of this data reduction system, see Marks and Strausser.* Figure 7 is a photograph of the SEADAC.

PROPOSED EXTENSION OF THE SEADAC

Even while the SEADAC is relatively new, some additional components are being considered which will: 1) increase its efficiency through saving of computational time; 2) extend its usefulness through new operations; and 3) prepare magnetic tape for re-use in the field.

Figure 8 is a block diagram showing the SEADAC, along with the proposed additions (dotted lines). The magnetic-tape recording brought from the field to the laboratory will be reproduced at 60 ips on a reel recorder, as before. Instead of re-recording, at 1-7/8 ips, on the loop recorder, this operation is performed on another reel recorder. The benefits derived from the addition of a reel recorder are twofold: 1) all the information on the reel may be transcribed in one re-recording; 2) the loop recorder is always free to play data into the analyser; no time is lost in the re-record process. A magnetic-tape signal eraser

will be incorporated to remove the signals from the original tape after it is transcribed onto the other reel. The original tape is then sent back into the field for re-use. The transcribed data is then 1/32 of its original length and after being converted to loop form (appropriate to each run) it is ready for analysis. During the re-record period, the information is simultaneously transcribed on to graphic chart paper, as at present, and a "book" of the experiment is prepared and filed. After the loops are played through the analyzer they are also stored, as at present.

Two changes are planned for the analyzer; one is simple and direct, and the other requires some careful electronic engineering. As mentioned in the preceding section, the two most popular modes of SEADAC operation are computation of the spectral density function and computation of the total energy in the record. In the present system, these calculations can be made either successively on one analyzer or simultaneously on both analyzers. If each analyzer can be made to perform both operations simultaneously, analysis time will be cut in half. The way to accomplish this is to incorporate an additional power integrator and recorder into each analyzer. This was done experimentally with the existing equipment, and the result appears in Figure 9. The spectral density curve and integrated curve marked "A" represent successive analyses on a single analyzer, whereas the curves marked "A + B" represent simultaneous analyses with the addition of the power integrator and recorder of the other analyzer. The small differences are attributed to the different gains of the two systems and are corrected by the calibrations. The good agreement of the curves seems to justify the extension of the analyzer.
system in this direction.

Computation of cross spectra is not yet available through commercial analog electronic equipment, so this matter must be pursued at the user's level. Some cross-spectrum analyzers have been built, and at least one is known to be successful. Of the different methods of cross-spectrum analysis, the one prescribing simultaneous treatment of two different signals is most appealing. The SEADAC is tailored to adaptation of this method because of the two basic analyzers and the careful selection of matched filters, the all-important feature of this technique. With the addition of a pair of power integrators and recorders, as discussed above, the system will contain all of the necessary basic components. To complete the cross-spectrum analyzer, it will be necessary to incorporate electronic circuitry for phase-shifting the signals after filtering and for multiplying the signals after phase-shifting. These problems are being investigated.

After completion of the SEADAC, as described, there will be two alternative methods of treating data (Figure 8):

1. Auto-spectra
   a. The energy spectrum of each of two signals.
   b. The total energy in each of two signals.

2. Cross-Spectra
   a. The energy spectrum of each of two signals.
   b. The co-spectrum (in phase) of the two signals.
   c. The quad-spectrum (90° out of phase) of the two signals.

In the prospective form discussed in this section, the data-processing method employed by the SEADAC may be considered to be comprised of
three separate operations, as shown in Figure 8:

1. Data collection;
2. Data preparation;
3. Data analysis.

The sole interdependence of these operations is in the necessity for each operation to provide work for the succeeding operation. As long as each operation has data on which to operate, it is completely independent of the others.

It is possible that the system as outlined here will sometimes suffer from an imbalance because of the piling up of data in one operation and a dearth of data in another. Occurrences of this sort are difficult to assess in such a dynamic environment, and problems of this sort will have to be treated as they arise. It is believed that the system design (Figure 8) is capable of handling the present and near future workloads of the Model Basin insofar as they can now be determined.
AMPLITUDE MODULATION APPLIED TO THE SEADAC

The analyzer system of the SEADAC is essentially a beat frequency analyzer commonly encountered in the field of acoustics. That is, a pure carrier frequency is mixed in a certain way with the random signal (seakeeping event) being studied. The process of mixing the carrier with the random signal in order to assign amplitudes to the frequency components in the random signal is called amplitude modulation. The carrier frequency is called the modulated frequency, and the frequencies in the random signal are called the modulating frequencies.

In the SEADAC, the oscillator produces a range of frequencies between 97,000 cps and 122,000 cps. This generation of frequencies by the oscillator occurs in a continuous fashion so that the resulting modulated signal is always changing.

For the sake of simplicity, we shall deal with the modulation process which occurs at any particular instant of time and a modulating signal which is a single frequency; we will then generalize for the random signal.

Consider the unmodulated carrier signal to be

\[ a_c = A_c \cos \omega_c t \]  \hspace{1cm} (1)

where \( c \) means carrier and \( \omega \) is the frequency. The modulating signal combining with \( \omega_c \) is

\[ a_m = A_m \cos \omega_m t \]  \hspace{1cm} (2)

where \( m \) refers to the modulating signal and \( \omega_c \gg \omega_m \), for reasons not of interest here. The process of modulation results in a
The combination of Equations (1) and (2) into the form

$$a = A_c \cos \omega_c t + k_a A_m \cos \omega_m t \cos \omega_c t$$

$$(A_c + k_a A_m \cos \omega_m t) \cos \omega_c t$$

where $k_a$ is a proportionality factor which determines the maximum variation in amplitude for a given modulating signal $A_m$. The term $(A_c + k_a A_m \cos \omega_m t)$ is the envelope of the modulated carrier frequency in Equation (3).

A trigonometric expansion of Equation (3) results in the component separation of the modulated carrier frequency

$$a = A_c \cos \omega_c t + \frac{m_a A_c}{2} \cos (\omega_c + \omega_m) t + \frac{m_a A_c}{2} \cos (\omega_c - \omega_m) t$$

where $m_a = k_a A_m / A_c$ is called the modulation index and determines the degree or nature of the modulation as dictated by $A_m$ and $A_c$. A sample of a modulated carrier wave given by Equation (3) appears in Figure 10. The graph of Equation (5) is shown in Figure 11 as a frequency spectrum of the relative amplitudes of the component waves in the modulated signal.

Consider, now, an example where the oscillator generates a signal of 97,100 cps. The resulting frequencies in Figure 11 will be, from left to right: 100 cps; 97,000 cps; 97,100 cps; and 97,200 cps. If, then, a filter designed to pass only 97,000 cps receives the modulated signal, only that component which is the lower side band (difference frequency) may pass through the filter.

Examination of the term representing the difference frequency in Equation (4) shows that the amplitude of the lower sideband is proportional
to the amplitude of the modulating signal \( A_m \) because \( m_o A_c = k_o A_m \).

To generalize to the random signal, consider that a given carrier frequency will mix with all the components in the random signal, but only that component which produces a lower sideband (difference frequency) of 97,000 cps will pass through the filter.

It should be noted that filters are not as narrow as suggested here so that a 5-cps filter, for example, will be centered at 97,000 cps but will permit all difference frequencies between 96,997.5 cps and 97,002.5 cps to pass. The analog computer squares and averages all these frequencies and assigns this estimate of the spectral density to the appropriate \( \omega_m \) designated by the oscillator. As long as the spectrum is flat in this area, the estimate is good.
Figure 1 – Block Diagram of Autocovariance-Transform Digital Method of Energy Spectrum Analysis
Figure 2 – Block Diagram of the SEADAC
0.1L = 0.238 V
1° = 0.0388 V
0.12 rad/sec² = -0.0311 V
0.16 = 0.392 V
0.111 V

Figure 3 - Page of a "Book" Showing Records of Seakeeping Events Recorded on Magnetic Tape
Figure 4 – Energy Spectra of Several Seakeeping Events Analyzed by the SEADAC with the Numerically Computed Energy Spectra Superposed

Figure 4a – Pitch

Figure 4b – Roll
Figure 4c - Waves

Figure 4d - Strain (Port)
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Figure 10 – An Example of a Modulated Carrier Wave

Figure 11 – The Spectrum of the Relative Amplitudes of the Components of a Modulated Wave as a Function of the Frequency of Those Components
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