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A Procedure for Using Ship Tow-tank Data to Simulate Ship Motion and Inclusion of Perturbations

Daniel W. Steeneck, Timothy C. Krometis, and Robert H. Sturges

***Abstract*—With the use of tow-tank experiments, seakeeping data may be generated for ships of various classes using comprehensive instrumentation. This data gives ship designers the ability to determine the response of a ship to various sea conditions far in advance of its construction and launch. However, this data does not indicate the effects of those sea conditions on the individuals aboard that ship. In order to perform studies that quantify these effects, a 3-axis (roll, pitch, and heave) ship motion simulator (SMS) has been designed and built at Virginia Tech. Many times, the data used to drive the simulator is based on tow-tank experiments on scale-model ships. However, the duration of the time-series data from an individual tow-tank experiment may be too short to perform realistic studies with participants. Therefore, we have developed a method of concatenating the data from multiple tow-tank experiments in order to generate time-series data to drive the 3-axis simulator such that the simulator's seakeeping is consistent with that of the ship. Additionally, a procedure is presented to include high amplitude, high frequency waves to the time series data so that rouge waves may be simulated.**

***Index Terms*— sea state, signal processing, simulator, tow-tank**

I. Introduction and Problem Statement

THE study of humans performing tasking on ship at various sea conditions is an area of interest to ship designers and ship equipment/asset developers. Colwell [1] explains since ship complements (crew) have been decreasing in size over time, the value of each sailor has increased. Thus, for the purpose of sailor work design, discovering the sailor's response to sea motions is more important than ever.

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D. W. Steeneck is with the Grado Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA 24063 USA (email: steeneck@vt.edu)

T. C. Krometis, was with the Grado Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA 24063 USA. He is now at Cognizant Technology Solutions, Teaneck, NJ 07666 USA (Tckrometis@gmail.com).

R.H. Sturges is with the Grado Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA 24063 USA (540)-231-7420; fax: (540) 231-3322; e-mail: sturges@vt.edu).

In order to perform realistic studies on human performance at various sea conditions, subjects must be tested in realistic conditions. Ideally, testing would be performed on the actual ship of interest in the required sea condition. Testing time on a ship is expensive and difficult to obtain. Moreover, the sea conditions cannot be controlled. On the contrary, a ship motion simulator (SMS) is affordable, available and can be controlled precisely. Some U.S. government labs (including SPAWAR[3], and Oakridge[4]) do have SMS's, however, they are designed primarily for equipment testing. Since no SMS exist to perform human testing to our knowledge, Virginia Tech built in-house a 3-axis SMS (roll, pitch, and heave).

The seakeeping characteristics of the ship of interest must be accurately simulated on the SMS in order to perform valid and realistic testing, These seakeeping characteristics are found in the acceleration data from testing. This data is gathered by comprehensive instrumentation, from sea-trials, or scale-model tow-tank testing. We focus on the data from tow-tank testing. The acceleration data gives the ability to determine the response of a ship to various sea conditions far in advance of its construction and launch. Using this data to drive our SMS, the effects of these sea conditions on human performance can be defined. The purpose of this paper is to provide methods of processing tow-tank seakeeping test data for use on a three-axis SMS. This processing requires three main steps: (1) Concatenation, (2) Perturbation inclusion, and (3) Sea Condition Modulation and Data-SMS synchronization.

The duration of the time series data from an individual tow-tank test may be too short to drive the SMS for any significant length of time. Thus, the time-series data from multiple tests of the same sea condition may be concatenated in order to drive the SMS for a longer duration while maintaining the validity of the time series produced. In fact, any length time series can be generated by this method to facilitate any testing duration requirements. Section II presents this method.

Additionally, the *Principles of Naval Architecture* resource [2] indicates that very high frequency, high amplitude waves ("rogue wave") are possible in certain sea states. This class of wave may not be observed in the tow-tank testing results and thus must be artificially generated. These types of waves will be referred to as balance perturbing waves, or *perturbations*. The generation of a perturbation is important so that *motion induced interruptions* (MIIs) and *motion induced fatigue* (MIF) can be studied. MIIs occur when the heave, pitch, roll, or some

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combination thereof is such that a person must take such a significant action to retain balance that his/her performance is impacted. On the other hand, MIF is a cumulative phenomenon characterized by a person's drop in performance due to the fatiguing effects of the sea condition. In Section III we present a method for including these perturbations in the simulation.

It may be the case that information on only one or two types of seas conditions is available, but one's research requires the simulation of other sea conditions. We will present a procedure to generate ship motion for any sea state by modulating the available data. Wave amplitude/frequency distributions from *Principles of Naval Architecture* [3] are used to determine the modulation parameters. Also, the sampling rates of the tow-tank data and the SMS might not be the same and so a procedure is presented to synchronize the two time series. Finally, using a similar procedure, the driver time-series for the SMS can be generated from the tow-tank time-series data. Section IV gives the methods for synchronizing two times series with different sampling rates.

II. CONCATENATING TOW-TANK RUNS

Results from tow-tank data comprise acceleration and pitch/roll angle time series data sampled at a constant rate. The acceleration time series data is provided in units proportional to m/s^2, or f/s^2. Typically, the units are in g's, or proportions of roughly 9.8 m/s^2 (32.2 f/s^2). The acceleration data must be doubly integrated over time in order to acquire position data.

The data will not typically give the initial conditions for the velocity and position. However, it can be assumed that over the course of a test the average velocity (in terms of heave) is 0 m/s and that the average position is 0 m, or a flat sea. We may subtract off some amount of velocity and some amount of position, from the resultant velocity and position time series such that these assumptions are satisfied.

Consider some heave time series acceleration data, $A_g(t)$. Assume the data is in g's and the data sampling rate is ts. Then to perform the above process first convert $A_g(t)$ to units of m/s^2.

$$A(t) = A_g(t)/9.81$$

Then integrate over time to get velocity (we use the triangle method).

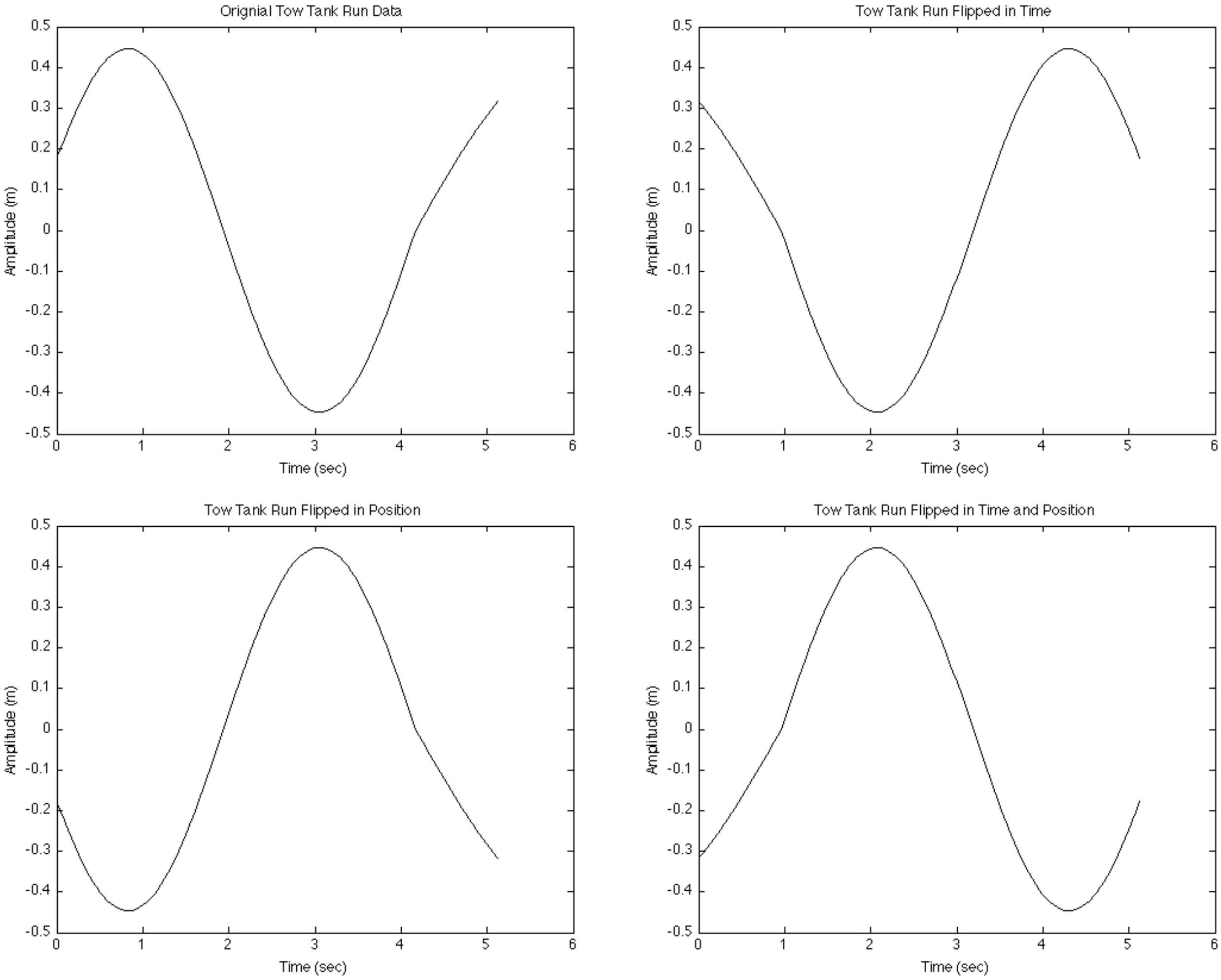

Figure 1. Possible operations on tow-tank data

$$V_0(t) = \sum_{i=0}^{T-1} A(i) * ts + \frac{1}{2\big(A(i+1) - A(i)\big)} * ts$$

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where *ts* is the time between data points. Since we assume that the average velocity is 0 *m/s* we must subtract the average of $V_0(t)$, $\overline{V_0(t)}$, from $V_0(t)$:

$$V(t) = V_0(t) - \overline{V_0(t)}$$

We perform similar operations to get P(t), the heave position of the ship.

$$P_0(t) = \sum_{i=0}^{T-2} V(i) * ts + \frac{1}{2\big(V(i+1) - V(i)\big)} * ts$$

$$P(t) = P_0(t) - \overline{P_0(t)}$$

Sometimes it is the case that ship motion data from one run of a tow-tank test does not produce a time-series long enough to drive the simulator for an adequate duration. Thus a method has been developed solving this problem by the process of concatenating position time series data of separate, independent, tow-tanks tests of the ship performed under the same conditions.

The number of tow-tank tests performed under the same conditions can be small. In order to generate a sufficient number of position time series to concatenate, we permit the following operations on a position time series:

1. Reverse data in time
2. Reverse data in position
3. Reverse data in time and position

These operations are illustrated in Fig. 1.

The justification for the validity of these operations is the frequency and amplitude characteristics of the position data are not being affected (i.e. the Bode plots for each of these operations will be identical).

Note that performing these operations on all the tow-tank runs effectively increases the number of tow-tank tests by a factor of 3. We will call the collection of original tow-tank runs and modified runs as T.

In order to create a longer duration run to drive the simulator using these short duration runs, a run is chosen at random and then subsequent runs are appended in turn. The procedure is given in detail, with illustration, below.

Notation

T : Collection of tow-tank runs and modified tow-tank tests

ρ_{mod}, $\rho^{a}{}_{mod}$, $\rho^{v}{}_{mod}$, $\rho^{p}{}_{mod}$: Tow-tank run to modify and its respective acceleration, velocity, and position time series data.

$\rho_{mod} \in$ T

ρ_{next}, $\rho^{a}{}_{next}$, $\rho^{v}{}_{next}$, $\rho^{p}{}_{next}$: Next tow-tank test to append and its respective acceleration, velocity, and position time series data.

$\rho_{next} \in$ T

$\rho^{p}{}_{new}$: Generated ship motion position data; created from concatenating tow-tank tests. Initially, $\rho^{p}{}_{new}$ will be empty.

v_{mod}^{final}: Final velocity of tow-tank run to modify

$v_{next}^{initial}$: Initial velocity of the next tow-tank run to be "stitched".

δ_v: Maximum value of the absolute value of the difference between v_{mod}^{final} and $v_{next}^{initial}$.

M: Maximum amplitude of $\rho^{p}{}_{new}$. This value is typically either the physical limit of the SMS or the maximum significant wave height for the sea condition being investigated.

Procedure

1. Randomly select initial run

Randomly select an initial run from T and denote it as ρ_{mod} as shown in Fig. 2.

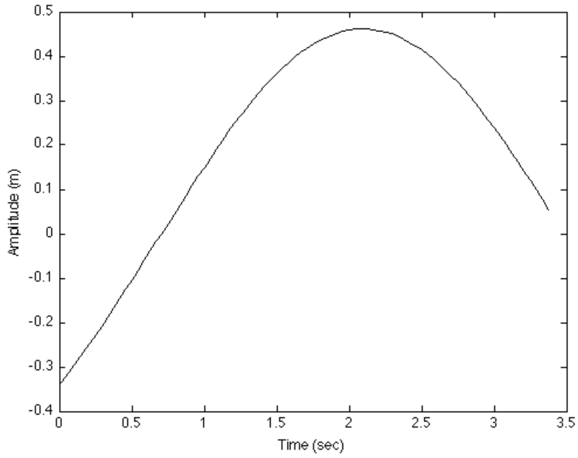

Fig. 2. Initial run

2. Select subsequent run

Find the average slope of the last 1 or 2 seconds of ρ_{mod} and call this v_{mod}^{final}. Randomly select elements from *T* until one is found such that δ_v is satisfied. Call this run ρ_{next} (Fig. 3) and its initial slope as $v_{next}^{initial}$.

Shift in position ρ_{next}^{p} so that it's initial position is equal to the final position of ρ_{mod}^{p}.

Check to see that the maximum amplitude, *M*, is not exceeded by any point in ρ_{next}^{p} . If it is, repeat step 2 until *M* is not exceeded.

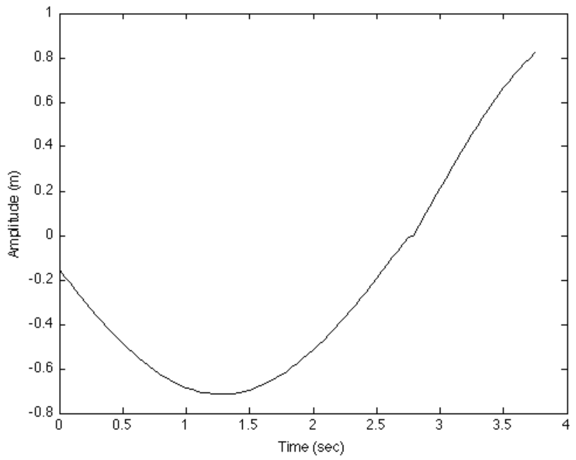

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Fig. 3. Next run

3. Match slopes and positions

Inevitably, v_{mod}^{final} and $v_{next}^{initial}$ will be not be equal. Thus we add a very small acceleration to the corresponding acceleration data ρ_{mod}^{a} so that $v_{mod}^{final} = v_{next}^{initial}$. This acceleration is $\frac{(v_{next}^{initial} - v_{mod}^{final})/ts}{\#\rho_{mod}^{a}}$, where *ts* is the sampling rate of the tow-tank data and $\#\rho_{mod}^{a}$ is the number of data points in ρ_{mod}^{a}. Then set ρ_{mod}^{p} equal to the double integral over time step, *ts*, of ρ_{mod}^{a} considering its initial conditions. See Remark 1 for a derivation of this slope matching procedure. Fig. 4 shows the resulting curve with the added acceleration.

Check to see that the maximum amplitude, *M*, is not exceeded by any point in ρ_{mod}^{p}. If it is, then repeat step 2

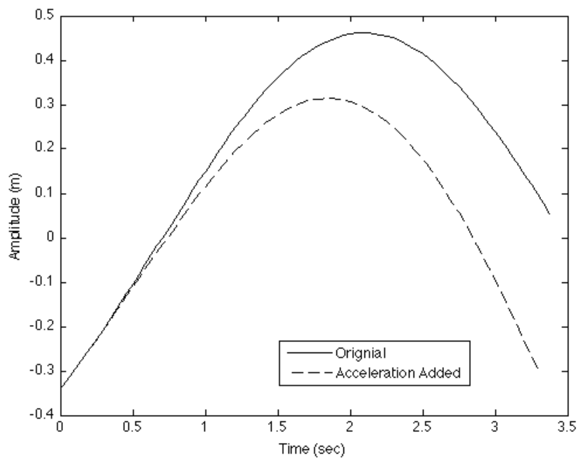

Fig. 4. Adding acceleration to initial run

4. Append run

Append ρ_{mod}^{p} to ρ_{new}^{p} and call this as ρ_{new}^{p}. Shift in position ρ_{next}^{p} so that its initial position is equal to the final position of ρ_{new}^{p}. Set ρ_{mod} as ρ_{next}.

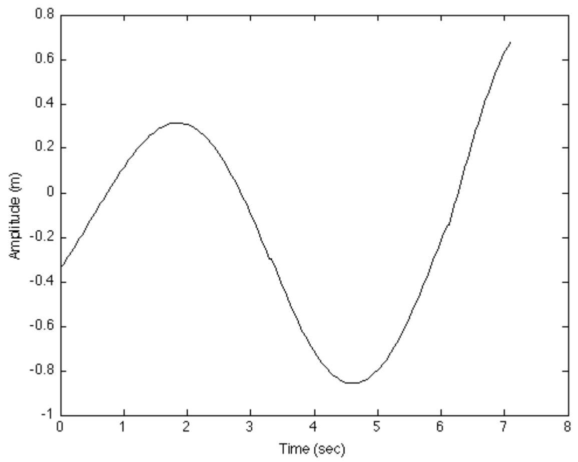

Fig. 5. ρ_{new}^{p} after 2 waves appended

5. Repeat

Return to step 2 and continue appending runs until some specified duration, *D*, has been exceeded. Truncate ρ_{new}^{p} so that it is of duration *D*. The resulting time series can be seen in Fig. 5.

6. Smooth Data

Smooth the data by using a method such as moving average or exponential smoothing.

7. Apply appropriate scaling factors

Since the data is gathered from a scale model ship in a tow-tank, use the appropriate scaling factors for the ship of interest and the tow-tank conditions.

There are some possible errors in the implementation of this procedure. Firstly, in Step 2 it might not be possible to find $\rho_{next} \in T$ with an initial slope less than or equal to δ_v from ρ_{mod}. If this is the case, then one must increase the value of δ_v. Additionally, it is possible that this code will enter an infinite loop if it is not possible to meet the maximum amplitude criteria. If this happens, then either increase the value of *M* or reduce the amplitude of the tow-tank data.
Roll and pitch may be handled in a similar manner.

Remark 1. Derivation of slope matching additional acceleration.

Since v_{mod}^{final} and $v_{next}^{initial}$ are not equal, a small acceleration, *a*, may be added to each data point in ρ_{mod}^{a} to affect the increase or decrease of v_{mod}^{final} such that $v_{next}^{initial} = v_{mod}^{final}$. Thus the sum of the additional accelerations must equal the difference between the slopes.

$$\sum_{0}^{\#\rho_{mod}^{a}-1} a * ts = v_{mod}^{final} - v_{next}^{initial}$$

or

$$a = \frac{(v_{next}^{initial} - v_{mod}^{final})/ts}{\#\rho_{mod}^{a}}$$

where $\#\rho_{mod}^{a}$ is the number of data points in ρ_{mod}^{a}.

III. Perturbations

Due to the short duration of the tow-tank time series data, the time series generated from the concatenation procedure may not fully represent the sea condition of interest. Namely, rogue waves might not be observed. To account for these rogue waves, the amplitude and frequency of segments of the concatenated time series can be modified.

The generated perturbations are consistent with the characteristics of the sea conditions described by the wave frequency-amplitude distributions in *Principles of Naval Architecture* [3]. After taking a specified time step, the nearest trough is identified and its subsequent period is modulated by frequency and amplitude to create a perturbation. Trough to trough, this process is repeated through the entire time series. Perturbations of any magnitude, frequency and time step desired can be added into the time series. Each subsequent time

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step can be generated randomly if desired. For subject testing, perturbations will reflect the largest waves potentially experienced during a given sea state.

1. *Identifying troughs*

Identify the troughs in the tow-tank time series by using a function that identifies and returns minimum values in the time series. The output from that function is shown in Fig. 6.

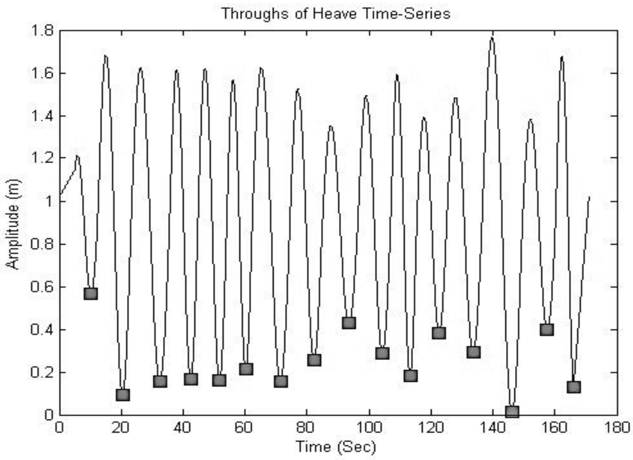

Fig. 6. Troughs in heave time series

2. *Identifying perturbation segments*

An interval at which to create the perturbations is determined based on testing requirements. The troughs nearest to multiples of the interval length are identified, and will be used as the start point for the perturbations. End points are identified as the subsequent trough after the start point.

3. *Modifying magnitude and frequency of perturbation segments*

To modify the magnitude of the wave, each segment of the time series between start and end points are shifted so that the minimum point of each segment has amplitude of zero. A multiplication factor is then applied to each of the perturbation segments to increase the magnitude. Using the method described in Section 4, the frequency of the segment is modulated as desired. These modified segments then replace the original segments, which can be seen in Fig. 7.

4. *Repetition on different time series*

Perform steps 1 through 4 on each of the heave, pitch, and roll tow-tank time series with the designated parameters for each type of movement. All time series are modified separately to maintain independence across the three degrees of freedom.

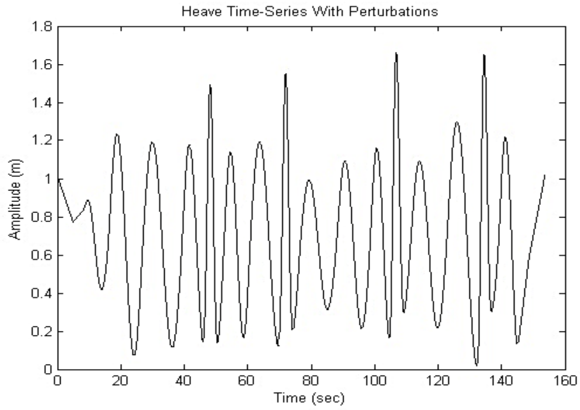

Fig. 7. Resulting heave time series with perturbations

IV. SEA CONDITION MODULATION AND SYNCHRONIZATION OF TOW-TANK DATA WITH SIMULATOR

In the case that tow-tank data for only one sea state is available, it is still possible to simulate higher and lower sea states. This is accomplished through increasing or decreasing both the period and amplitude of the simulated ship motion (Section 2) by an appropriate scaling factor. We used the tables on pages 27 and 28 of *Principles of Naval Architecture* to arrive at these scaling factors. We will now give a procedure for modulating the simulated ship motion given data for only one sea condition and the aforementioned scaling factors.

First we will present the method for frequency modulation. Let ρ^p_{orig} be our original simulation data and ρ^p_{mod} be the modulated simulation data. Let s_{orig} be the average period of, and s_{mod} be the target period of ρ^p_{mod}. Then s_{orig}/s_{mod} will be the proportion of data points more (or less) the original data will contain than the modulation if the sampling time of the simulation is constant. For example if we have ρ^p_{orig} comprising 10,000 points, then ρ^p_{mod} at 1/2 the period has only 5,000 points. We will use this s_{orig}/s_{mod}as our "data point index step length" to establish where in the original simulation data to look for a data point to insert into the modulated data.

Formally, let $\#\rho^p_{orig}$ be the number of data points in the original time series. Let $\#\rho^p_{mod}$ be the number of data points in the time series resulting from the modulation. Both time series will have the same sample rate. If we let index 0 correspond to the data point at time 0 for each of the time series, then we can compute the number of data points in ρ^p_{mod} as

$$\#\rho^p_{mod} = 1 + floor((\#\rho^p_{orig} - 1) * s_{mod}/s_{orig})$$

since the number of data points after the first one must be proportional to the ratio of the time series' periods.

For example, in the original time series, one period is completely captured by 5 data points of length 2 seconds; the time series is to be modulated such that it has period 6.25 seconds. Both time series will have sampling time ½ seconds. Thus the new time series has *1 + floor(4*6.25/2) = 13.* Note that the resulting time series will only create a time series of length 6 seconds.

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We may estimate the value of the position between two data points of the original time series by interpolating. Let $Y_{orig}(t)$ be the position of the ship at time *t* of the original time series. Let $t_{orig}(i)$ be the time corresponding to the i^{th} data point of the original time series. If t is between $t_{orig}(i)$ and $t_{orig}(i+1)$, then

$$Y_{orig}(t) = \frac{Y_{orig}(t(i+1)) - Y_{orig}(t(i))}{ts} t + Y_{orig}(i).$$

Thus we can estimate $Y_{mod}(t)$ using $Y_{orig}(t)$ by the approximation:

$$Y_{mod}(t_{mod}(j)) \cong Y\_orig(t_{mod(j)} * s_{orig}/s_{mod}).$$

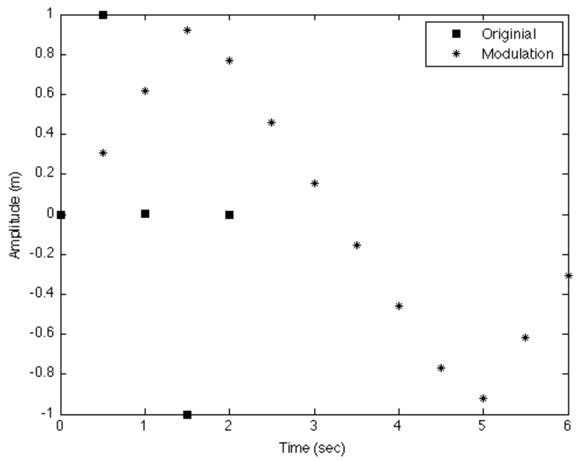

Fig. 8. Example modulation

Fig. 8 presents an example modulation of a 2 second period time series into a 6.5 second period time series.

In order to modulate the amplitude of the time series, one must just multiply the time series by A_{mod}/A_{orig}. A_{orig} is the average amplitude of the original time series and A_{mod} is average amplitude of the resultant modulated time series.

It may be the case that the sampling rate of the tow-tank data is not the same as the sampling rate of the controller on the simulator. In this case one must synchronize the tow-tank data to be used with the simulator. The procedure to do this is identical to the sea condition modulation procedure except s_{orig} is the sampling time of the simulator, and s_{mod} is the sampling time of the tow-tank data. For example, say the sampling time of the simulator is 1 second, but the sampling time of the tow-tank data is every 2 seconds. Then we'll need double (less 1) the number of data points in the tow-tank data by using interpolation to estimate the points between all adjacent data points.

V. Conclusions

Understanding how humans perform at sea is important and can be most easily studied using a sea motion simulator. The realistic testing of human subjects requires the realistic replication of ship motion on the simulator.

This paper provides the researcher using a SMS the procedures to drive the SMS using actual small-scale ship tow-tank testing data. Using a time series concatenation method, long duration time series can be generated from multiple short duration tow-tank tests. Next, the time-series can be modified to include waves not observed during tow-tank testing so that human subjects may experience them during testing. Additionally, even if data from multiple sea conditions are not available from the tow-tank testing, one can use the given modulation technique to generate any sea condition desired. Lastly, since the sampling time of the tow-tank data and SMS may not be the same, a method is provided to convert between sampling times.

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