| REPORT DOCUMENTATION PAGE | | | | Form Approved OMB No. 0704-0188 |
|---|---|---|---|---|



| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From - To)* |
|---|---|---|
| 06-30-2016 | Final report | 06-15-2013- 06-30-2016 |

**4. TITLE AND SUBTITLE**
Integrated High-Fidelity CFD/FE FSI Code Development and Benchmark Full-Scale Validation EFD for Slamming Analysis

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**
N00014-13-1-0616

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Grenested, Joachim L.

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Lehigh University
Packard Laboratory, 19 Memorial Drive West
Bethlehem, PA 18015

**8. PERFORMING ORGANIZATION REPORT NUMBER**
542945

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Office of Naval Research, 875 N. Randolph St., Arlington, VA 22203-1995
Reports also sent to: 1) ONR REG Office Chicago-N62880, 230 South Dearborn, Rm 380, Chicago, IL 60604-15955; 2) Defense Technical Information Center, 8725 John J. Kingman Road, Ste. 0944, Fort Belvoir, VA 22060-6218; 3) Naval Research Laboratory, ATTN: Code 5596, 4555 Overlook Avenue SW, Washington DC

**10. SPONSOR/MONITOR'S ACRONYM(S)**
ONR

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
16PR02886-00

**12. DISTRIBUTION/AVAILABILITY STATEMENT**

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
The ONR / Lehigh slamming load test facility, a.k.a. Numerette, was upgraded with more piezo-resistive film pressure sensors, single-point pressure sensors, accelerometers, an additional inertia navigation system, and LVDT's. New tests were performed in the Atlantic Ocean and further insight into slamming was gained. Three items were studied in more detail - vertical "rigid body" accelerations, the effect of bottom stiffness on slamming response, and wavelet analysis of slamming data. Data have been continuously provided to the University of Iowa where numerical analyses of the Numerette have been performed.

**15. SUBJECT TERMS**

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | Joachim Grenestedt |
| U | U | U | none | | 19b. TELEPHONE NUMBER *(Include area code)* (610) 758-4129 |

**Standard Form 298** (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

## INSTRUCTIONS FOR COMPLETING SF 298

**1. REPORT DATE.** Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

**2. REPORT TYPE.** State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

**3. DATES COVERED.** Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

**4. TITLE.** Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

**5a. CONTRACT NUMBER.** Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

**5b. GRANT NUMBER.** Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

**5c. PROGRAM ELEMENT NUMBER.** Enter all program element numbers as they appear in the report, e.g. 61101A.

**5d. PROJECT NUMBER.** Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

**5e. TASK NUMBER.** Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

**5f. WORK UNIT NUMBER.** Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

**6. AUTHOR(S).** Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES).** Self-explanatory.

**8. PERFORMING ORGANIZATION REPORT NUMBER.** Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES).** Enter the name and address of the organization(s) financially responsible for and monitoring the work.

**10. SPONSOR/MONITOR'S ACRONYM(S).** Enter, if available, e.g. BRL, ARDEC, NADC.

**11. SPONSOR/MONITOR'S REPORT NUMBER(S).** Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

**12. DISTRIBUTION/AVAILABILITY STATEMENT.** Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

**13. SUPPLEMENTARY NOTES.** Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

**14. ABSTRACT.** A brief (approximately 200 words) factual summary of the most significant information.

**15. SUBJECT TERMS.** Key words or phrases identifying major concepts in the report.

**16. SECURITY CLASSIFICATION.** Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

**17. LIMITATION OF ABSTRACT.** This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

# REPORT OF INVENTIONS AND SUBCONTRACTS

*(Pursuant to "Patent Rights" Contract Clause) (See Instructions on back)*

*Form Approved OMB No. 9000-0095 Expires Jan 31, 2008*



**PLEASE DO NOT RETURN YOUR COMPLETED FORM TO THE ABOVE ORGANIZATION. RETURN COMPLETED FORM TO THE CONTRACTING OFFICER.**

| | |
|---|---|
| 1.a. NAME OF CONTRACTOR/SUBCONTRACTOR | Lehigh University |
| c. CONTRACT NUMBER | N00014-13-1-0616 |
| b. ADDRESS (Include ZIP Code) | 526 Brodhead Avenue<br>Bethlehem, PA 18015 |
| d. AWARD DATE (YYYYMMDD) | 20130615 |
| 2.a. NAME OF GOVERNMENT PRIME CONTRACTOR | Office of Naval Research |
| c. CONTRACT NUMBER | |
| b. ADDRESS (Include ZIP Code) | 230 South Dearborn, Rm 380<br>Chicago, IL 60604-1595 |
| d. AWARD DATE (YYYYMMDD) | |
| 3. TYPE OF REPORT (X one) | a. INTERIM ☐ b. FINAL ☒ |
| 4. REPORTING PERIOD (YYYYMMDD) | a. FROM 20130615<br>b. TO 20160630 |

## SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR (If "None," so state)

| NAME(S) OF INVENTOR(S) (Last, First, Middle Initial) a. | TITLE OF INVENTION(S) b. | DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c. | ELECTION TO FILE PATENT APPLICATIONS (X) d. (1) UNITED STATES (a) YES | (1) UNITED STATES (b) NO | (2) FOREIGN (a) YES | (2) FOREIGN (b) NO | CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (X) e. (a) YES | e. (b) NO |
|---|---|---|---|---|---|---|---|---|
| none | | | | | | | | |

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR

| (1) | (2) |
|---|---|
| (a) NAME OF INVENTOR (Last, First, Middle Initial) | (a) NAME OF INVENTOR (Last, First, Middle Initial) |
| (b) NAME OF EMPLOYER | (b) NAME OF EMPLOYER |
| (c) ADDRESS OF EMPLOYER (Include ZIP Code) | (c) ADDRESS OF EMPLOYER (Include ZIP Code) |

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

| (1) TITLE OF INVENTION | (2) FOREIGN COUNTRIES OF PATENT APPLICATION |
|---|---|
| | |

## SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR (If "None," so state)

| NAME OF SUBCONTRACTOR(S) a. | ADDRESS (Include ZIP Code) b. | SUBCONTRACT NUMBER(S) c. | FAR "PATENT RIGHTS" d. (1) CLAUSE NUMBER | d. (2) DATE (YYYYMM) | DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e. | SUBCONTRACT DATES (YYYYMMDD) f. (1) AWARD | f. (2) ESTIMATED COMPLETION |
|---|---|---|---|---|---|---|---|
| none | | | | | | | |

## SECTION III - CERTIFICATION

7. CERTIFICATION OF REPORT BY CONTRACTOR/SUBCONTRACTOR (Not required if: (X as appropriate)) ☐ SMALL BUSINESS or ☒ NONPROFIT ORGANIZATION

I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.

| a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL (Last, First, Middle Initial) | b. TITLE | c. SIGNATURE | d. DATE SIGNED |
|---|---|---|---|
| Rice, Dolores B. | Contract and Grant Specialist | Dolores B. Rice | 7-11-16 |

# Final Report

# Integrated High-Fidelity CFD/FE FSI Code Development and Benchmark Full-Scale Validation EFD for Slamming Analysis

Award number N00014-13-1-0616 (June 15, 2013 – June 30, 2016)

Joachim L. Grenestedt
Department of Mechanical Engineering & Mechanics
Lehigh University
19 Memorial Drive West
Bethlehem, PA 18015, USA
Phone: +1-610-758 4129
email: jog5@Lehigh.edu

September 30, 2016

**Abstract**

The ONR / Lehigh slamming load test facility, a.k.a. Numerette, was upgraded with more piezo-resistive film pressure sensors, single-point pressure sensors, accelerometers, an additional inertia navigation system, and LVDT's. New tests were performed in the Atlantic Ocean and further insight into slamming was gained. Three items were studied in more detail - vertical "rigid body" accelerations, the effect of bottom stiffness on slamming response, and wavelet analysis of slamming data. Data have been continuously provided to the University of Iowa where numerical analyses of the Numerette have been performed.


**Fig. 1.** The Numerette in operation. The boat was designed for 23 G vertical acceleration.

## Technical Section

Three issues were studied in more detail: vertical accelerations, how bottom stiffness affects slamming, and wavelet analysis. These are described in three separate sections below.

## Vertical Accelerations

Slamming loads are typically of high intensity but very short duration. A ship undergoing slamming thus experiences high (vertical) accelerations but only for a short duration. The peak acceleration is difficult to capture with less than a high speed data acquisition system and appropriate mounting of the accelerometers. The measured accelerations will depend strongly on what structure the accelerometers are attached to; accelerometers mounted directly on bottom panels of the Numerette regularly see accelerations on the order of 1000 $m/s^2$ (100 G), whereas an accelerometer mounted on a compliant deck of a boat will see significantly lower accelerations. The Numerette has a stiff stainless steel "skeleton", Fig. 2, which is well suited to mount accelerometers to and measure "rigid body" accelerations. Two of these "rigid body" accelerometers are shown in Figs. 3 and 4.

The response from one of the "rigid body" accelerometers during a slamming event is shown in Fig. 5. In this graph are shown the raw data from the accelerometer, as well as plots of the data filtered with a 500 Hz and a 100 Hz low pass filter, respectively. The transverse bulkhead where this accelerometer was mounted is very stiff so the measured accelerations are not affected much by local vibrations. The three top graphs indicate that the "true" vertical acceleration was on the order of 15-20 G. The acceleration was also estimated with a finite difference of the vertical velocity from the INS, which also lead to a vertical acceleration in this range.

An estimate of the accuracy of the measurements as well as of the stiffness of the hull can be obtained by using measurements (accelerometer and gyro data) from one location of the boat to predict behavior at a different location. In Fig. 6 is shown vertical velocity at bulkhead #5 obtained in two different ways: by time integrating the output from an accelerometer mounted on bulkhead #5, as well as by using accelerometer and gyro data from sensors on bulkhead #2 and extrapolating (assuming a rigid hull) to bulkhead #5. The two estimates match exceptionally well.

The data shown are fairly typical from operating the Numerette in speeds up to 28 m/s and in sea states up to 4 (significant wave height 1.25-2.5 m). It appears reasonable to conclude that vertical "rigid body" accelerations of the Numerette often are in the 15-20 G range. This is considerably higher than the vertical accelerations to which high speed boats according to ABS and DNV need to be designed at present.

Since 2010 when the Numerette was sea launched it has experienced one extreme slam when 50 G accelerometers were saturated. Strains measured at the top and bottom flange of one of the bottom longerons are shown in Fig. 7. "Regular" slams occurred around 99.2 s, 99.8 s, and 101 s. Then at 102.1 s was the extreme slam. Note that the strain of the top flange (red in the graph) does not return to zero after the slam. The reason is that the flange was plastically deformed. The strain recovery, on the order of $\sigma_y/E$=0.2%, is indicated in the figure. The hull was designed to 25 G so it should be no surprise that the structure underwent permanent deformation during this 50+ G slam.

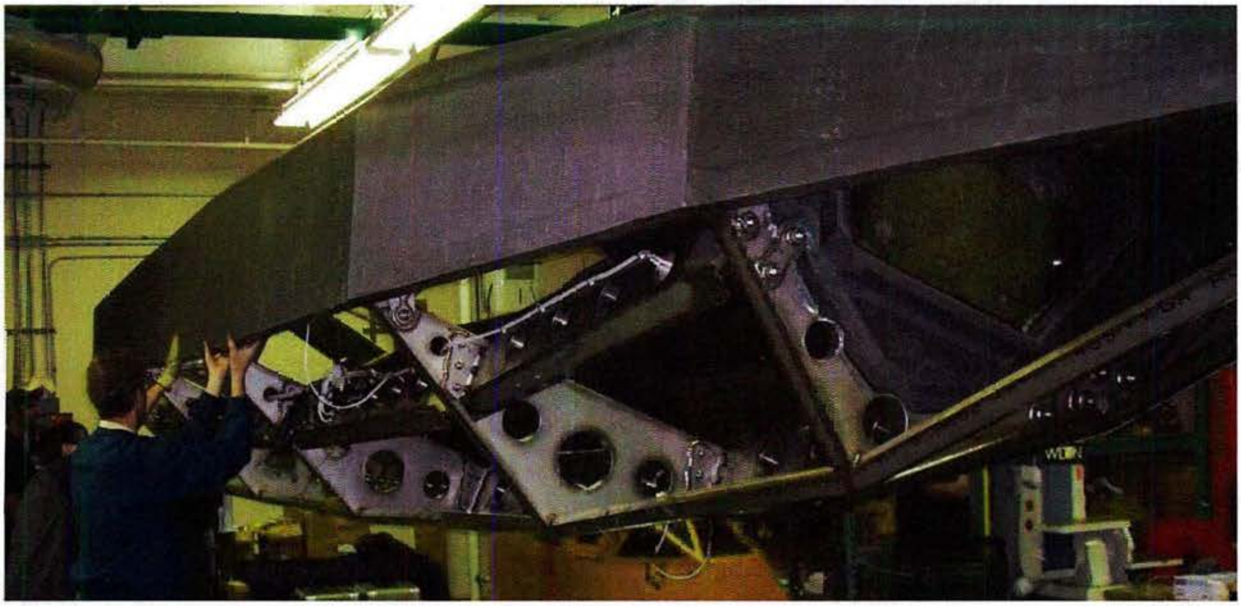


**Fig. 2.** The stainless steel skeleton shown during manufacturing of the Numerette. The bulkhead towards the right in the photo is #5, followed by #4 to #1 to the left. Bulkhead #1 is the transom.

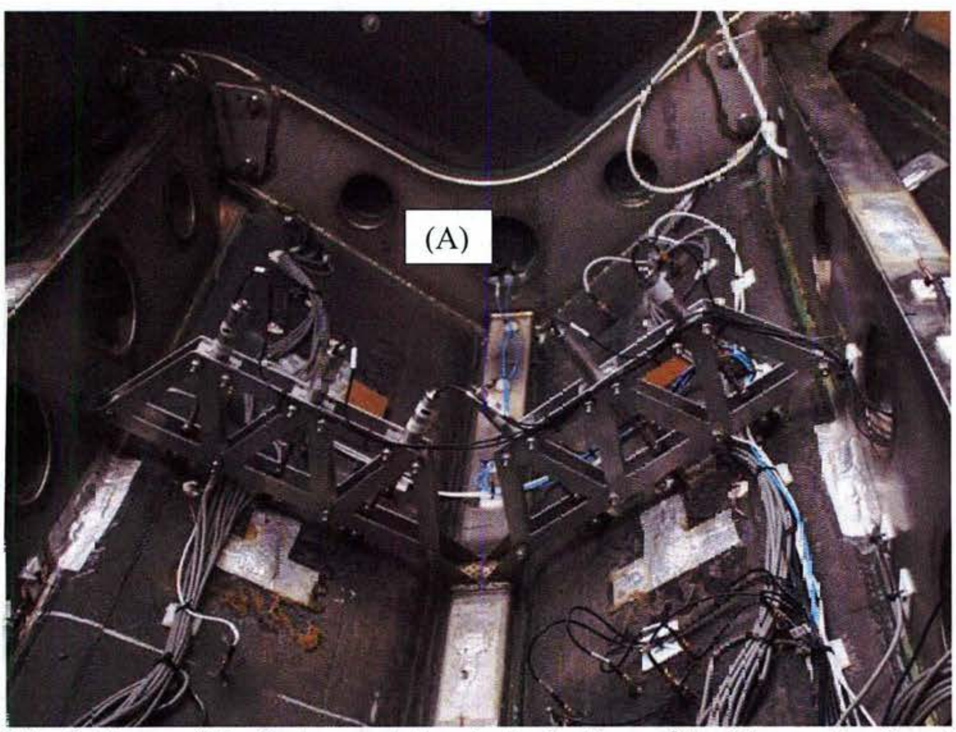



**Fig. 3.** Some of the instrumentation in the bottom of the Numerette. One "rigid body" accelerometer is mounted at (A) in the transverse bulkhead #5.

**Fig. 4.** Two INS modules, a triaxial piezoelectric accelerometer and a single-axis MEMS accelerometer, mounted on the transverse bulkhead #2 just in front of the engine.

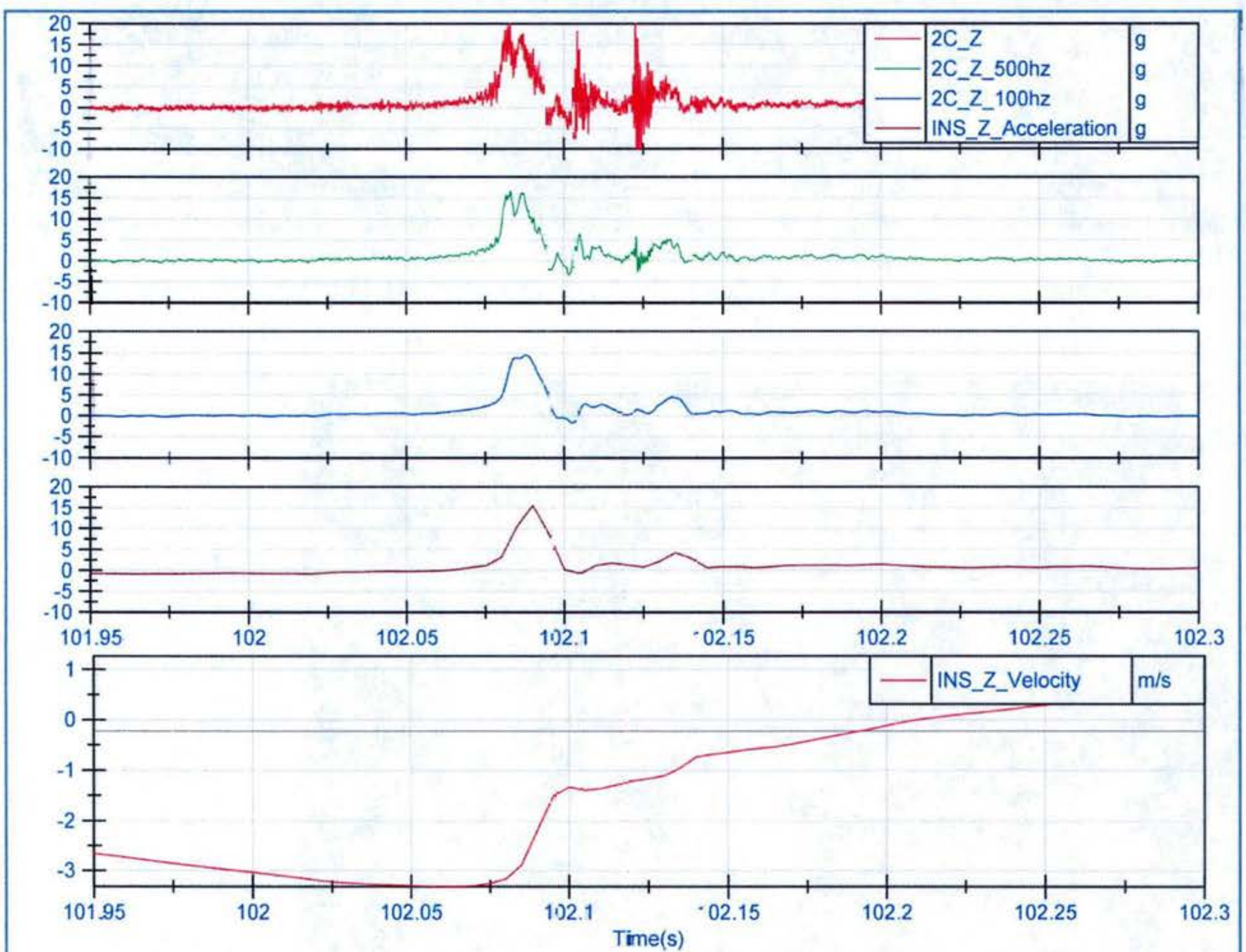



**Fig. 5.** Response from one of the "rigid body" accelerometers. The top graph shows the raw data, the second is the same data but filtered with a 500 Hz low pass filter, the third is also the same data as the first but filtered at 100 Hz. The fourth graph is the acceleration as estimated with a finite difference of the vertical velocity from the INS, and the last is the vertical velocity from the INS

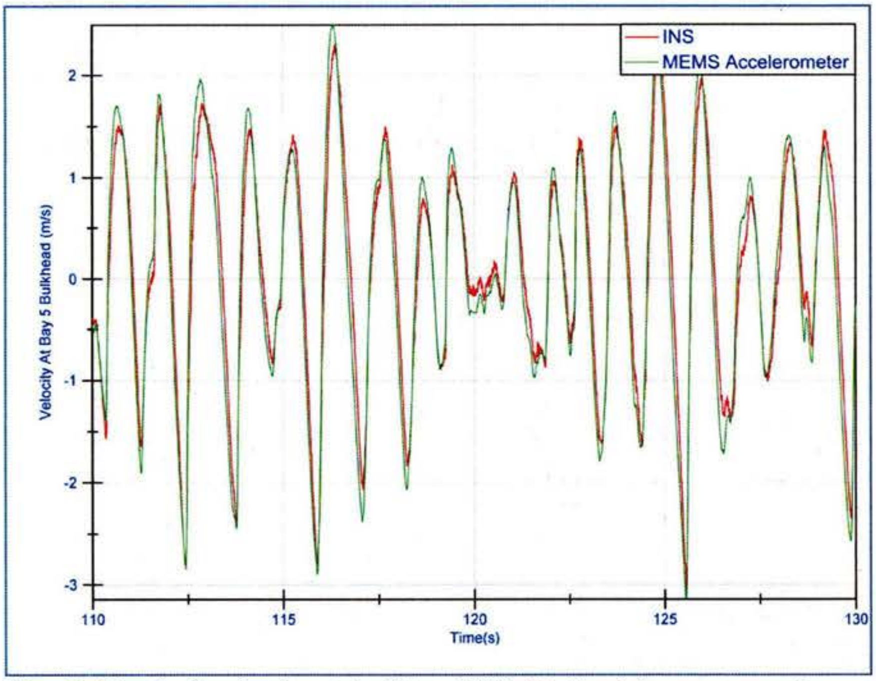



**Fig. 6.** Vertical velocity at bulkhead #5 obtained from an accelerometer located on the bulkhead, as well as from extrapolating data measured at bulkhead #2.

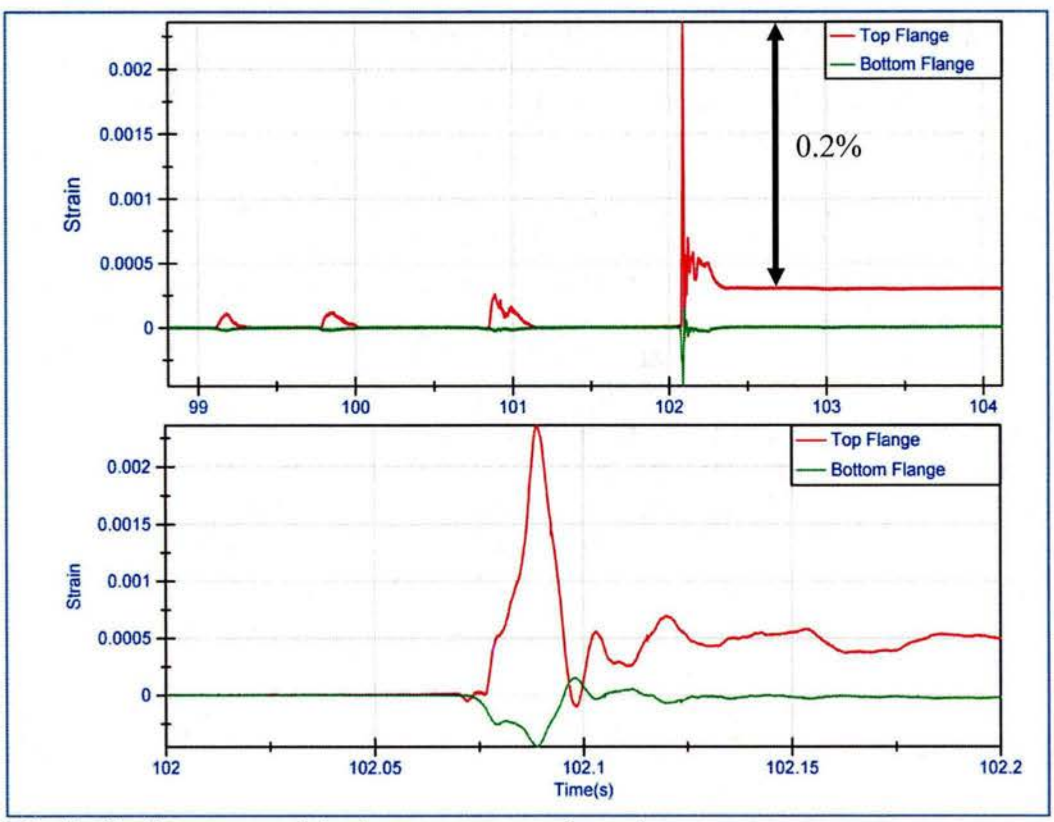



**Fig. 7.** Strain measured during an extreme slamming event.

**Effect of Bottom Stiffness on Slamming Response**

The bottom of the Numerette was made of ten composite sandwich panels, most of them with different properties. In particular, starboard and port panels had different layups and thus different stiffnesses and/or mass. This was done in order to be able to study the effect that bottom stiffness has during slamming.

The Numerette was outfitted with a large number of sensors, including externally mounted piezo-resistive film pressure sensors, through-hole bottom pressure sensors, strain gages, LVDT's, accelerometers, etc. Some of the sensors are shown in Fig. 3. Strain gages were mounted on the inside of the outer composite skin during the manufacturing of the bottoms panels, whereas strain gages on the inner skin were adhesively bonded onto the panels after installation in the boat. Strain gages were watertight sealed under the silver tapes in Fig. 3. The strain gage locations are shown in Fig. 8. Some of the LVDT's are shown in Fig. 3 and some of the externally mounted film pressure sensors are shown in Fig. 9.

The bottom stiffnesses were characterized by static and dynamic means. Static loads were applied at 21 locations on each segment of a bottom panel (for example between transverse bulkheads, keel and longeron) and deflections were measured using six LVDT's, Figs. 3 and 10. The ratio between port and starboard pointwise stiffnesses is shown for bay 4 (between bulkheads #4 and #5) in Fig. 11. The port bottom panel was approximately 1.6 times stiffer than the starboard panel.

Modal analyses were also performed on bottom panels. The panels in bay 4 were hit at 75 locations with an instrumented impact hammer and the response was measured using accelerometers, Fig. 12. Frequency Response Functions (FRF) were synthesized and showed good agreement with measured data, Fig. 13.

The Numerette was then operated in the Atlantic Ocean. A typical strain history is shown in Fig. 14. Fast Fourier Transforms (FFT) of strain data obtained from strain gages mounted on starboard and port panels are shown in Fig. 15. The ratio between amplitudes at a given frequency varies from approximately 1.4 at lower frequencies to approximately 1.2 at higher frequencies. Probability distributions are shown in Fig. 16.

A simple relation between bottom stiffness and response during slamming should not be expected. A much simplified analytical study of slamming has been performed by Lv and Grenestedt [1,2]. The load was modeled as a stepwise moving pressure and the bottom panel was modeled as a 1D beam. In spite of these simplifications, the response follows a complicated relation with respect to stiffness, Fig. 17.

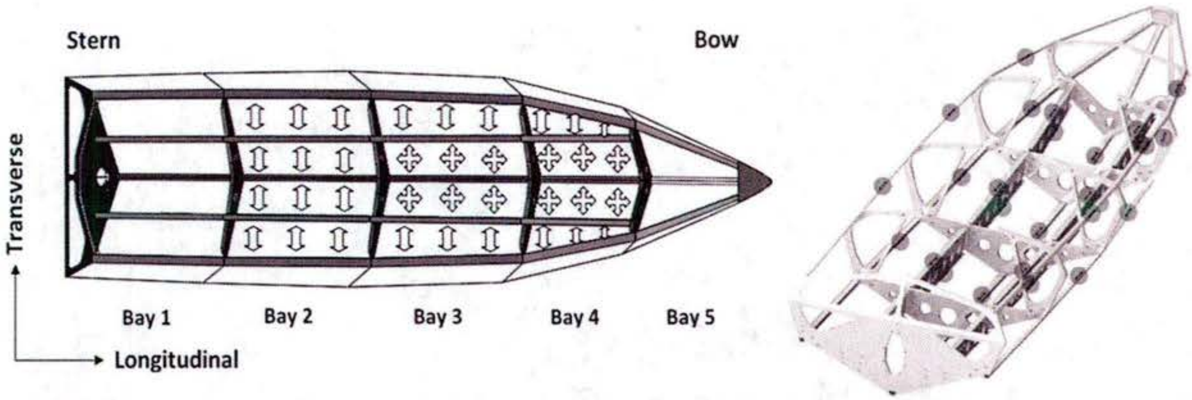



**Fig. 8.** Strain gage locations. Left: strain gages on composites sandwich bottom panels. Right: strain gages on stainless steel skeleton. Arrows indicate directions of strain gages.

**Fig. 9.** Externally mounted film pressure sensors.

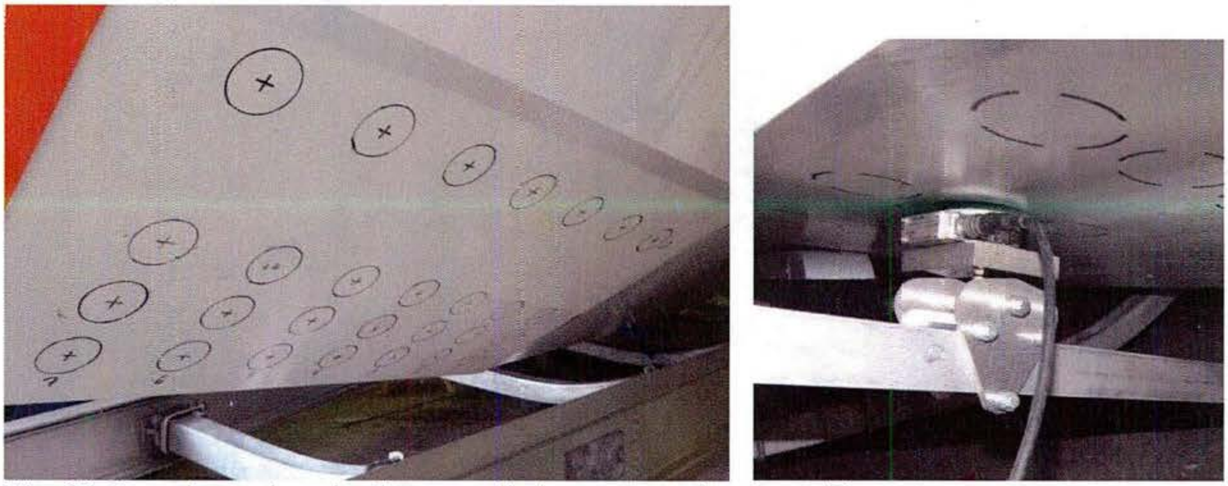


Fig. 10. Locations where load was applied to measure bottom stiffness.

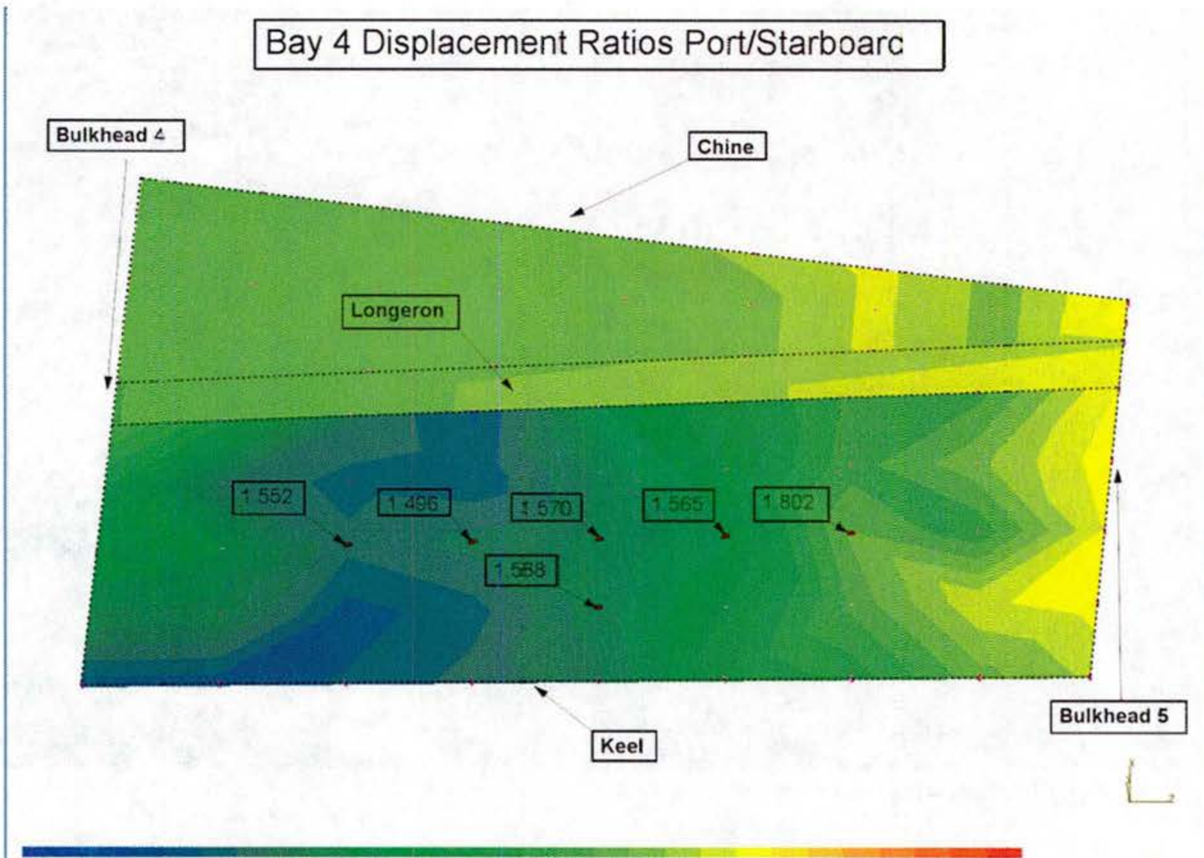



Fig. 11. Ratic of pointwise stiffness (load/deflection) for port and starboard panels between bulkheads #4 and #5.

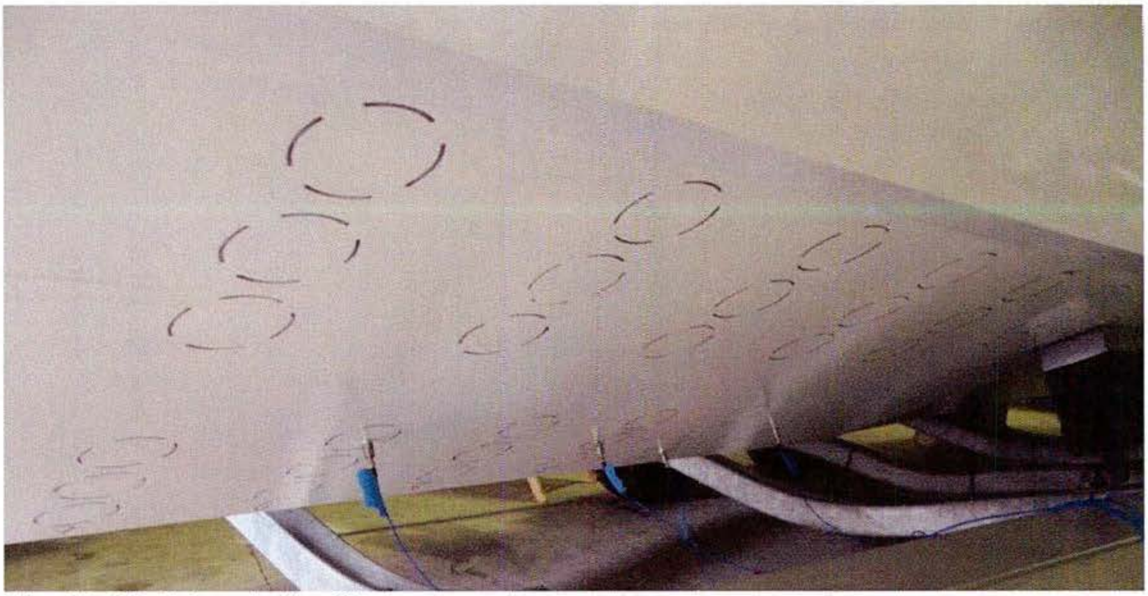


**Fig. 12.** Modal analysis of bottom panels.

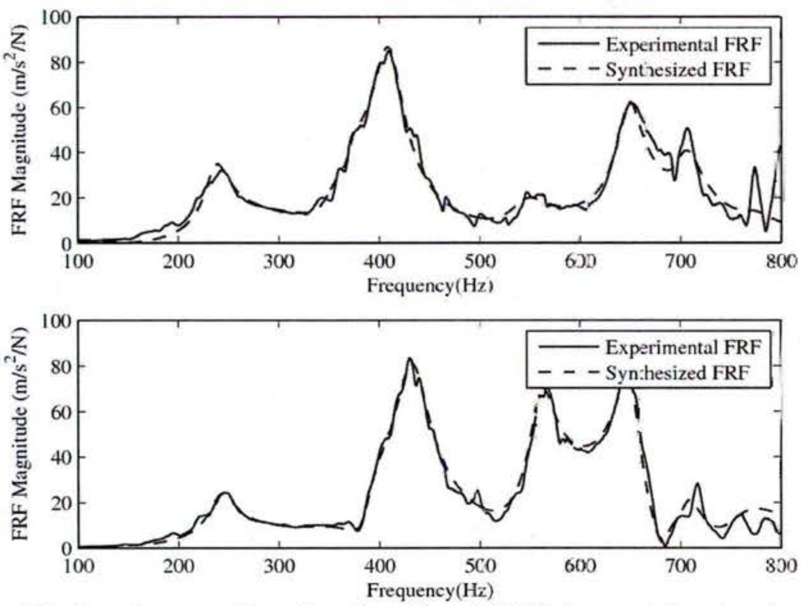




**Fig. 13.** Accelerance (acceleration/force) FRF for port (top) and starboard (bottom) panels.

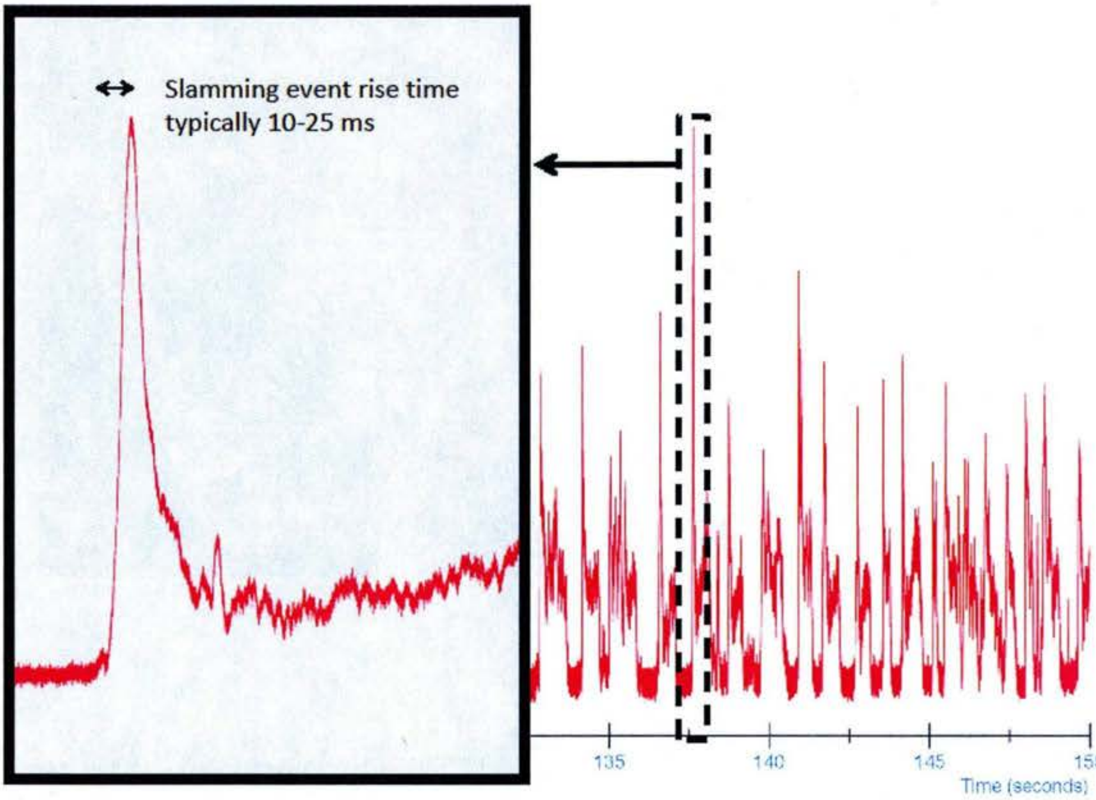



**Fig. 14.** Strains during typical slamming events. Slams in this case occurred approximately once per second. The rise time of strain was typically 10-25 ms.

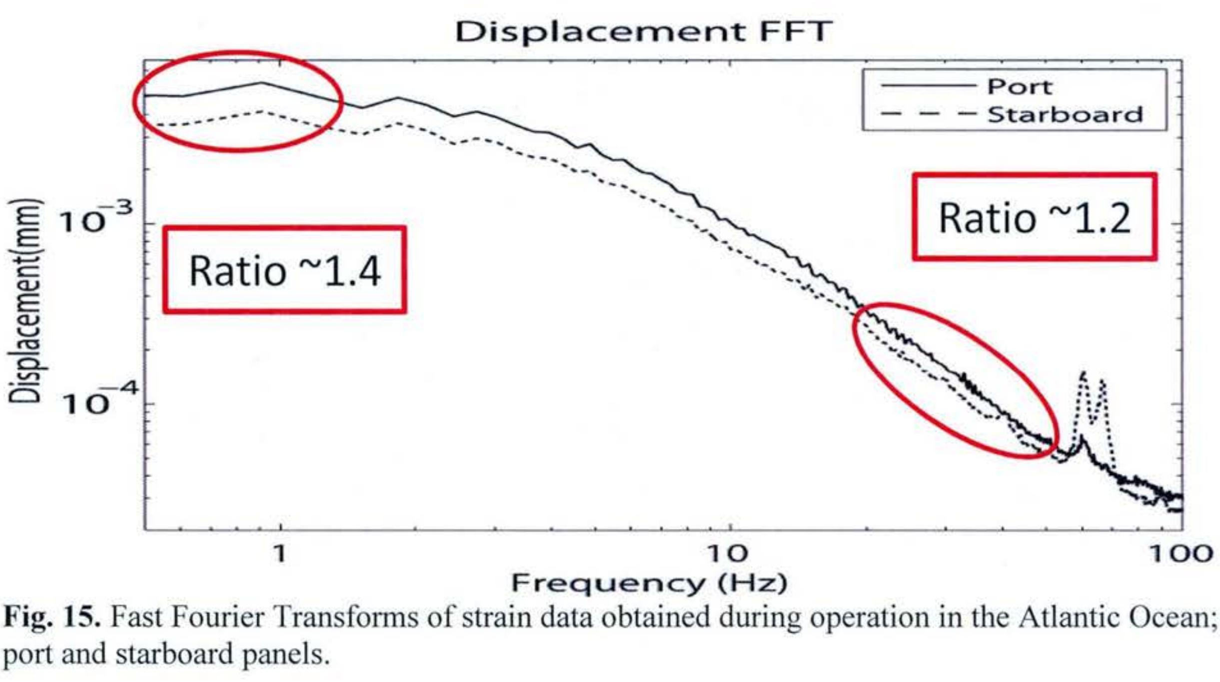
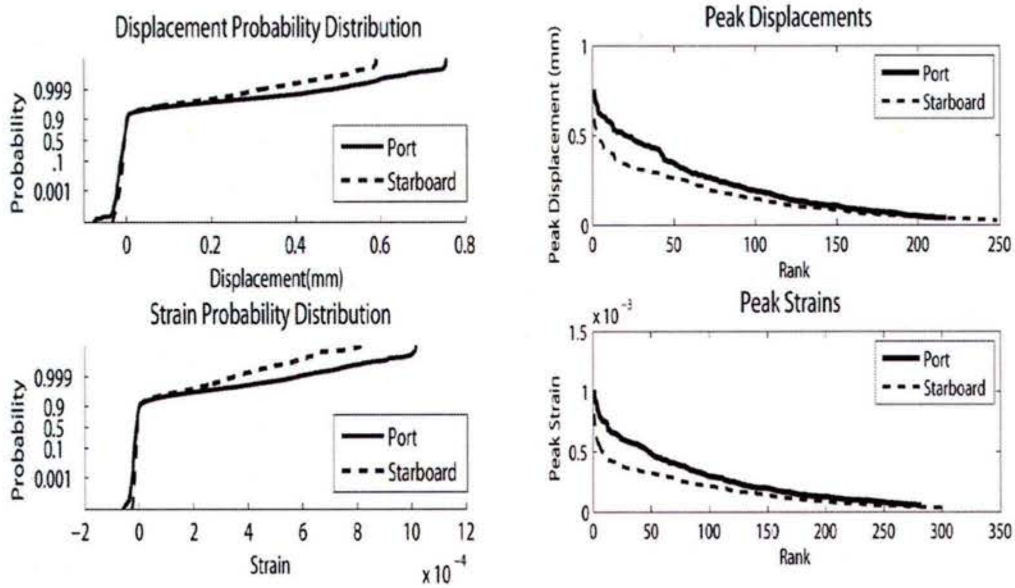


**Fig. 15.** Fast Fourier Transforms of strain data obtained during operation in the Atlantic Ocean; port and starboard panels.




Displacement at 99th percentile, ratio: 1.40
Strain at 99th percentile, ratio: 1.48
Displacement, mean of 1/3 peaks, ratio: 1.46
Strain, mean of 1/3 peaks, ratio: 1.56

**Fig. 16.** Distribution of displacements and strains.

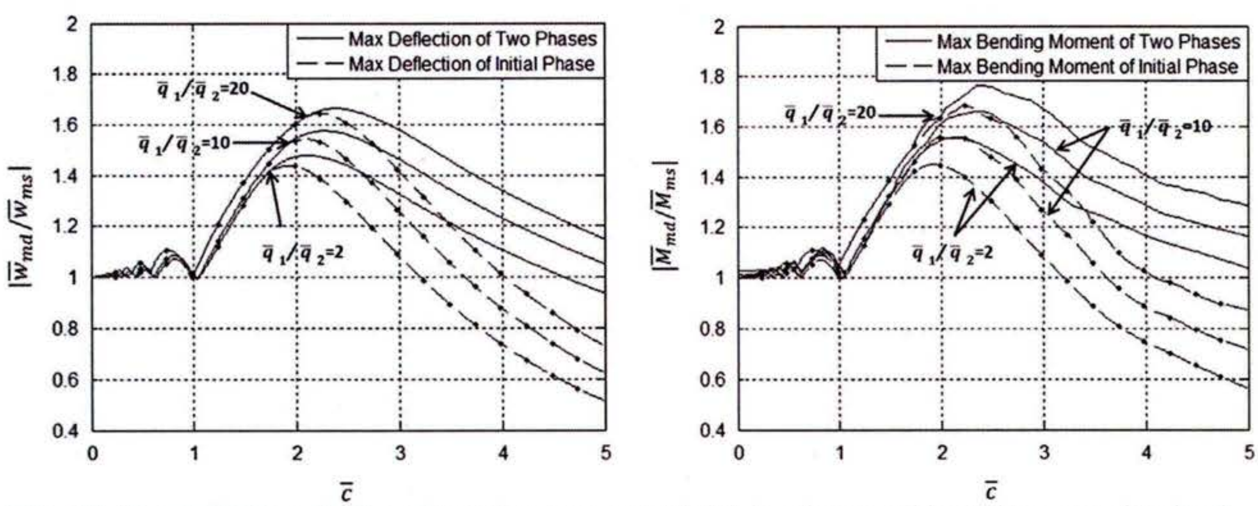



**Fig. 17.** The deflection (left) and bending moment (right) in a beam subjected to a moving load (Lv and Grenestedt [1-2]).

**Wavelet Analysis**

This section outlines some results which indicate the usefulness of wavelet analysis for slamming. Fig. 18 shows output from an accelerometer mounted on a bottom panel in bay 4. A slam occurred at 0.6 s; the question is happened just after 0.5 s. An FFT of the signal, Fig. 19, does not appear to reveal any significant information. However, a wavelet plot, Fig. 20, shows some interesting features. Just after 0.5 s there is significant frequency content around 400 Hz, which is close to the dry eigenfrequency of the panel, Fig. 13. It appears reasonable to believe that just after 0.5 s the panel is still dry and that it vibrates at its dry natural eigenfrequency. This agrees with Fig. 21, which apart from the accelerometer signal shows strains at three different locations along the length of the boat. There is a strain peak at 0.36 s in bay 2, then another just after 0.5 s in bay 3, and finally a third one just after 0.6 s in bay 4. What happened is that the boat was airborne and reentered the water near the transom first. The pressure spike from slamming thus traveled from the rear of the boat towards the bow. The acceleration seen just after 0.5 s in bay 4 is believed to be a result of the water slamming onto the bottom panels in bay 3. This slam shook the hull and lead to the (dry) vibrations of the bottom panels in bay 4 just after 0.5 s.

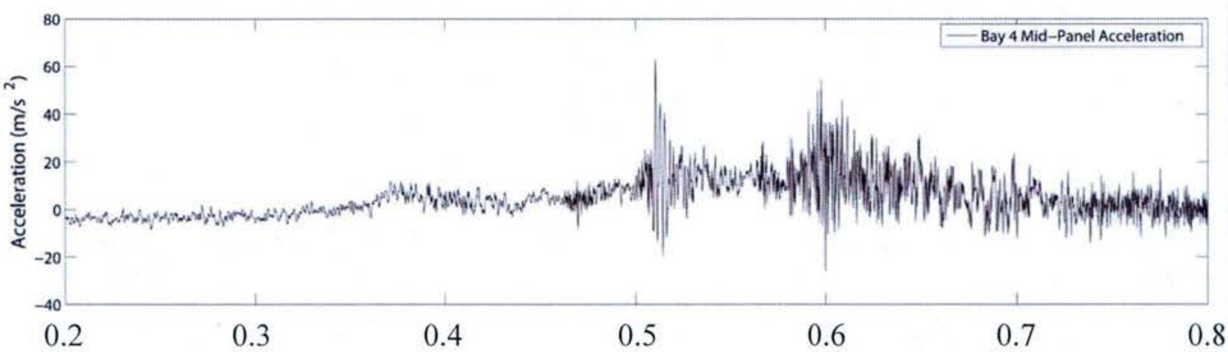



**Fig. 18.** Typical acceleration from an accelerometer in bay 4. The slam occurred at 0.6 s.

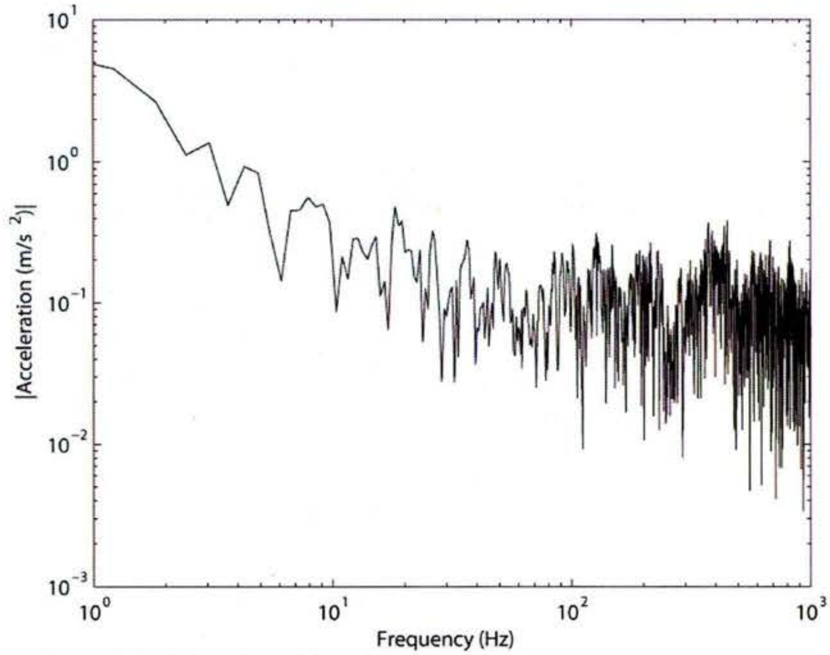



**Fig. 19.** FFT of the signal in Fig. 18.

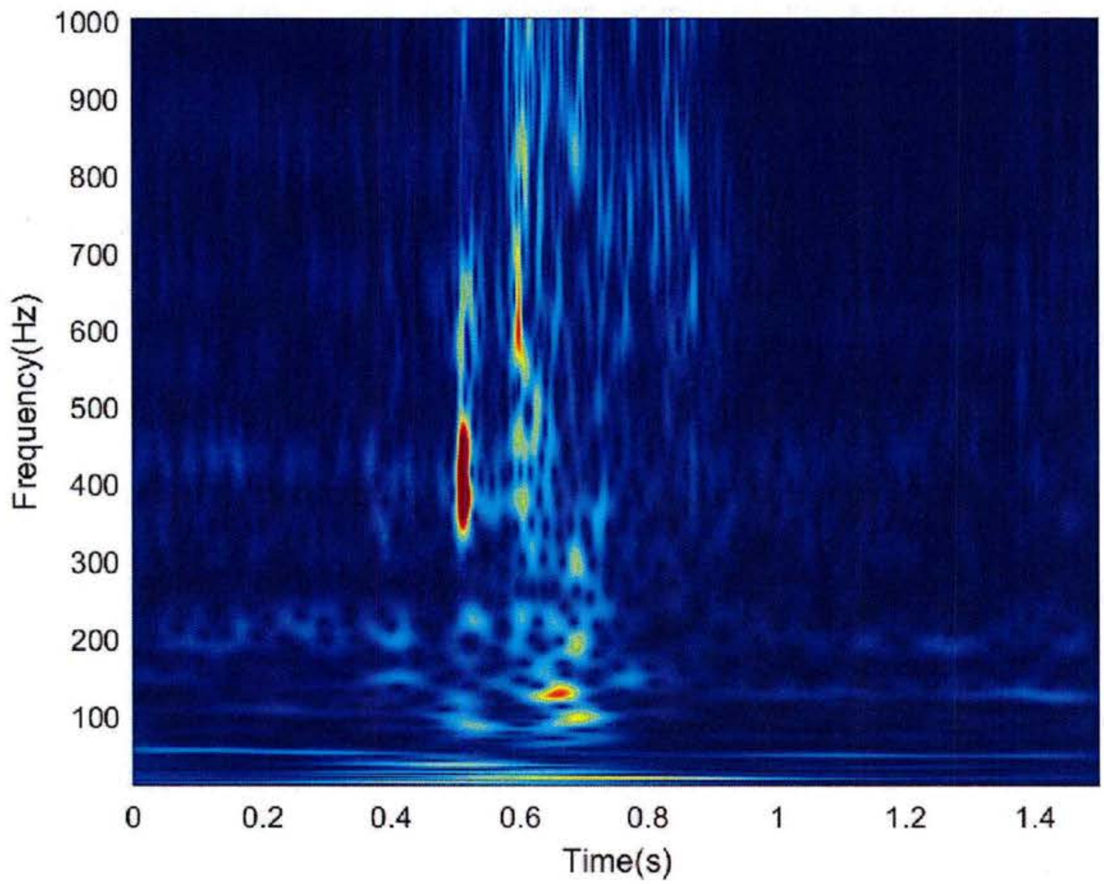



**Fig. 20.** Wavelet plot of the signal in Fig. 18.

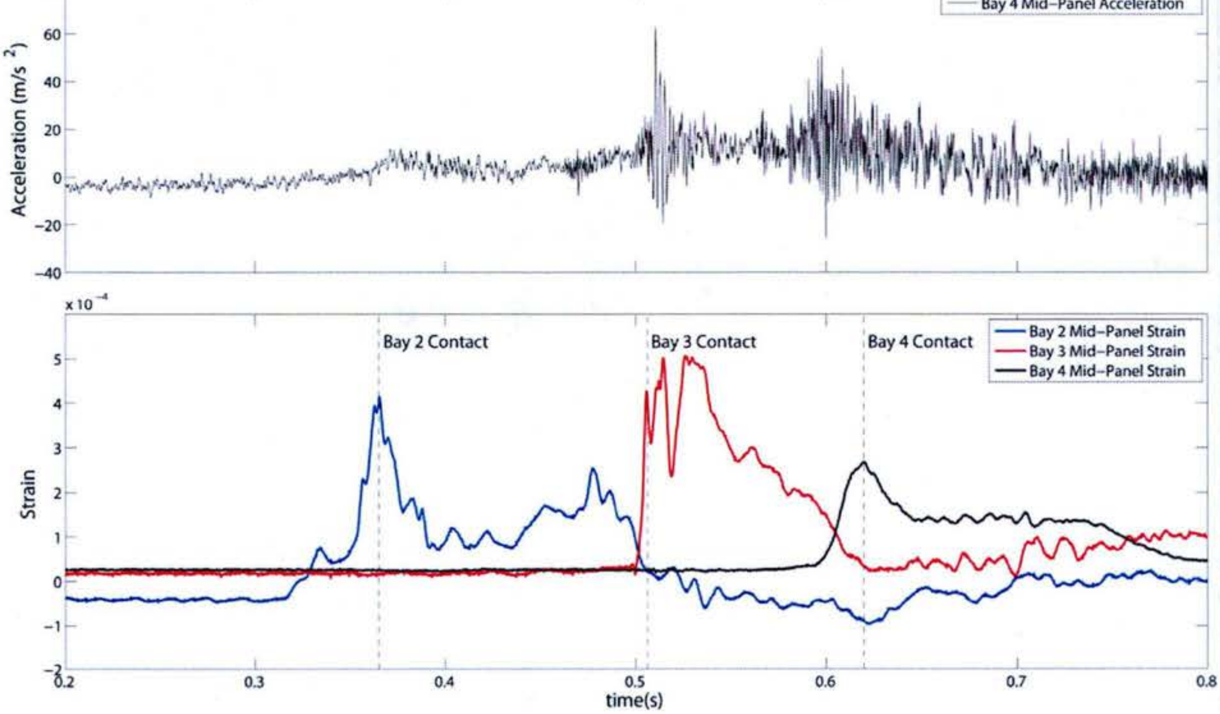



**Fig. 21.** Acceleration (top) and three strains (bottom).

## Summary and Conclusions

The Numerette was successfully operated at multiple occasions in the Atlantic Ocean. Analyses of experimentally measured accelerometer data indicate that this boat experiences rigid body accelerations far beyond what is presently prescribed in codes for design (ABS, DNV). Analyses of experimental data from a starboard and a port bottom panel with different stiffness indicate that the response does not directly scale with the stiffness ratio. Finally, wavelet analyses were used to study the response from some accelerometers and it was concluded that wavelets may be very useful in the study of slamming.

## References

1. Lv, J., Grenestedt, J.L., "Some Analytical Results for the Initial Phase of Bottom Slamming," Marine Structures, Vol. 34, 2013, pp. 88-104.

2. Lv, J., Grenestedt, J.L., "Analytical study of the responses of bottom panels to slamming loads," Ocean Engineering, 94, 2015, pp. 116-125.