REVIEW

Slamming of ships: where are we now?

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Literature published on the problem of ship slamming in waves is reviewed from the point of view of someone working at a ship research institute. Such an institute is confronted with rather practical questions regarding the acceptability of certain design parameters such as the acceptable amount of bow flare angle for use at sea. The importance of these questions is illustrated by noting that actual slamming or the presumed danger of slamming is the main reason for ship operators to reduce speed or to change heading. The review shows that such questions cannot yet be answered. The problem of the local effect of the impact is very complicated owing to the importance of air inclusions, bubbles in the water, compressibility of water and cavitation effects. Only a computational method properly including all these effects will give an accurate answer; also model tests will not be capable of doing this, if only because the methods to extrapolate the results of models to full scale are not yet developed. The problem of the global response of the ship to a wave impact is closer to being solved. A two-stage approach is proposed, consisting of a computational fluid dynamics method for individual impacts and an approximate method to be included in long-term simulations. However, to arrive at a realistic long-term distribution, one has to account for the seamanship of the captain; avoiding the worst conditions or adapting the ship speed and course has a large effect on the actual extremes. Research on this topic has hardly begun.

Keywords: slamming; wave impacts; boundary-element method; statistical method; scaled experiments; full-scale measurements

1. Introduction

If we define the start of slamming research as the publication of von Kármán’s paper in 1929, the topic is now a healthy 82 years old and still going strong. The subject is still far from being solved, so we might expect a good many years to come. The interest in this subject from the scientific community has had some ups and downs, but in general it is rather steady, resulting in an impressive amount of papers; more than 1000 papers were listed in the Ship Structure Committee report.*

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One contribution of 13 to a Theme Issue ‘The mathematical challenges and modelling of hydroelasticity’.
SSC-385 [1]. Recent years have seen some of the ‘ups’ being caused by serious ship accidents, sometimes with a significant loss of life. The accident with the ferry Estonia in 1994 jumps immediately to mind and, more recently, in 2007, the accident with the container ship MSC Napoli. The latter incident clearly showed that slamming and slamming-induced whipping are not yet soundly incorporated in the rules of Class societies; even today, an estimated factor of the maximum bending moment is used to account for these dynamic effects.

This review is written from the point of view of a consultant working for a ship research institute. The mission of the research institute is to apply and extend hydrodynamic knowledge for the maritime industry. This means that there is always a view to practical applications rather than pure fundamental research. The most important question that the research institute needs to answer on slamming is: is a certain amount of bow flare for a certain ship on a particular route acceptable or not? Much more specific, but essentially the same question is: what does a large bow flare mean in terms of the need to reduce speed in adverse conditions? These questions are much more important than the question of the ultimate slamming load.

In writing this review, use has been made of some excellent reviews written in the past. Publications that can be mentioned are Henry & Bailey [2], the International Ship Structure Conference (ISSC) Committee II.3 report Slamming and impact [3], the Society of Naval Architects and Marine Engineers (SNAME) Panel HS-2 review by Dalzell et al. [4], Daidola & Mishkevich [1], Mizoguchi & Tanizawa [5], Faltinsen [6] and more recently Faltinsen [7], Faltinsen et al. [8] and finally Hirdaris & Temarel [9]. This review is somewhat different in the sense that the focus is not on the details of theoretical methods, but rather on the possibilities for practical application of a certain theoretical approach. The sections in this review focus on the different approaches.

2. The importance of slamming

Accidents are not the only focus of attention for work on the subject of slamming. It has been recognized for a very long time that slamming is the primary reason for voluntary speed reduction for ships sailing in head or bow-quartering seas [10]. As such, it affects the arrival time of the ship and therefore the economy, and, if the master decides to avoid a heavy weather area, it also affects the fuel required for a certain voyage [11].

The main reason why ship captains reduce speed to avoid slamming is the fact that the peaks of slamming forces have a peculiar probability of exceedance distribution. If we use a three-parameter Weibull distribution, defined as \( \text{Pr}(x > a) = e^{((x-a)/a)^\beta} \) to fit peaks of data, we are used to a Rayleigh distribution (\( \beta = 2 \)) for linear processes and to an exponential distribution (\( \beta = 1 \)) for quadratic processes. Slamming peaks have a distribution with even lower values of \( \beta \); a consequence of this is that extreme values are really extreme: the slamming force associated with a probability of exceedance of \( 10^{-4} \) can be three times higher than the slamming force at a probability of exceedance of \( 10^{-3} \). It seems plausible that it is this fact that makes the severity of slamming so unpredictable and that, therefore, operators are very cautious and react to incidental impacts by reducing speed.
Figure 1. Buckled areas (shaded) and a crack with a length of 10 m in the bow of a container ship.
Adapted from Yamamoto et al. [12].

Even mild slamming can introduce a whipping response of the ship’s hull. This results in, notably at the fore and aft end of the ship, high accelerations and a significant high-frequency contribution to the bending moment. The high accelerations cause increased loads on the lashings of a container ship, which ultimately might result in loss of containers overboard. The high-frequency contribution to the bending moment contributes to fatigue damage. It is recalled that bulk carriers have had many problems with fatigue damage, even to a point that complete panels in the side of the ship have disappeared. Today, bulk carriers use a monitoring system to check on fatigue damage and crack growth; in this way, they have a better control over the damage and the time interval needed between repairs. This way of monitoring might also be the future for other ship types like large container ships.

Severe slamming can cause damage owing to one single impact. Yamamoto et al. [12] reported damage owing to bow flare slamming on a small 819 twenty feet equivalent unit (TEU) container ship in cyclone conditions. The remarkable conclusion from the analysis of the damage and from the drop tests that were carried out with a two-dimensional model of Station (St) 18.5 of this ship showed that the pressure peaks were lower than expected—comparing with Wagner’s theory—but the duration of the high peak was much longer than expected. Yamamoto et al. concluded that the large impact consisted of a pressure of about 840 kPa on a circular area with a diameter of 13.7 m. This very high force caused buckling and cracks in the structure (figure 1).
An extreme event was experienced by the *Estonia* in 1994 when she lost her bow visor and damaged her watertight front door. This damage caused the ship to capsize and to sink in a relatively short time with loss of a large number of passengers and crew. The official report [13] indicates heavy slamming as the cause of losing the bow visor. It is very unfortunate that the cause for such a large accident is still being disputed, that sources of information regarding the accident are still not opened and that no convincing research has been carried out to analyse this drama.

The report on the accident with the *Napoli* [14] (figure 2), clearly revealed the state of the art in the Class rules with respect to the level at which whipping stresses are incorporated; just by a safety factor based on experience. Bureau Veritas made an effort to use an estimation method based on a strip theory approach ([14], Annex E), later published by Tuitman [15], and arrived at an estimated contribution of whipping to the maximum wave bending moment of 30 per cent. Later on, Storhaug [16] estimated that the whipping contribution could be anywhere between 20 and 60 per cent of the wave bending moment in the sea state at the time of the accident. To complicate matters further, doubts were raised about the role of the short-duration whipping stresses in the collapse mechanism of the ship’s structure.
3. Slamming, physical phenomena

A slamming event is characterized by a sudden high force of relatively short duration imposed on a body. This event occurs when a body enters a fluid with a small relative angle between the body surface and the fluid surface. In this case, the contact region between the fluid and the body surface expands at a high speed, even if the speed of the body motion is moderate. The classical explanation for the high pressure with the resulting force is the sudden acceleration of the fluid close to the interface.

The impact pressure is very dependent on the relative angle between the body and the fluid surface. This effect has been demonstrated by experiments with dropping wedges with a varying deadrise. In particular, when the relative angle becomes small, the pressure rises sharply, as illustrated in figure 3. When the relative angle is really low, below $5^\circ$, the impact phenomena become more complex. The air is being compressed below the body in the phase just before
the impact. This high-pressure region causes a depression of the fluid surface; therefore the body touches the fluid on the outer edges of the body in the first instance, in this way enclosing a volume of air. Compressibility effects of this volume of air play an important role in the pressure underneath the body. At a second stage of the impact, this volume of air will escape, and there will be direct contact of the body and the fluid. Compressibility effects of water might play a role, but also the elastic/plastic response of the structure of the body. It has been suggested that the dynamic response of a flat stiffened plate can cause local cavitation [6].

These complex phenomena create a problem in predicting full-scale values based on scaled experiments. For ‘normal’ impacts, when the relative angle between the body and the fluid is larger than 5°, it is commonly accepted that Froude’s Law of similitude holds. For flat impacts, if the relative angle is smaller than 5°, this is no longer the case (figure 4); the compressed air affects the slamming pressure, which means that the ambient pressure must be reduced for scaled tests. Although this will certainly improve the similarity of the phenomena during the scaled tests and at full scale, it is not sufficient, as discussed by Bogaert et al. [18].

4. Momentum theory

Momentum theory is the oldest theory to tackle the problem of slamming. The theory was initially applied to estimate forces on the floats of landing sea planes. Von Kármán [19] was the first to use the change in the added mass of the floats as an estimate of the impulsive force. The concept of added mass was already
Figure 5. Vertical bending moment on a destroyer in waves. Experimental result (solid line) and calculated result (dashed line) using the momentum theory of Leibowitz [22].

well known in those days. Von Kármán based the added mass of the float on the added mass of a flat plate with finite width; only the vertical velocity was used in the force estimation.

The work of von Kármán attracted the interest of other researchers, who improved his method. Pabst [20] used the vertical velocity normal to the float to calculate the change in impulse, and in this way, the forward velocity was included. Pabst already stated that, if the structure of the plane and floats were infinitely stiff, the forces would be infinitely high; in other words, the capability of the sea plane to survive a landing on water depends on the flexibility of the connection to the floats. This statement is of course only true if a flat plate impacts horizontally on water and if the effect of the water surface being depressed by the air underneath the plate is neglected; but Pabst’s realization of the importance of a flexible structure for the floats is worth noting.

Perhaps the most well-known paper on momentum theory is that by Wagner [21]. In contrast to the more intuitive papers mentioned previously, Wagner’s approach was more mathematical, using potential flow theory. He used the analogy of the impacting float with the flow around a wing at incidence. In this way, the problem of the impact was linked to a planing vessel. The years following Wagner’s work showed very little progress in the development or application of momentum theory. One of the problems was the calculation of added mass for ship sections, for which computers were required. The lack of computer power was clearly illustrated by Leibowitz [22] who reported on the slamming forces on a Dutch destroyer. The ‘measurement’ consisted of a series of still photographs of the ship in waves. From these stills, the ship motion and the parameters of the encountered wave were derived. The added mass of the ship sections was calculated using Prohaska’s method [23] for different drafts. Using a system of tables, the added mass and the relative velocity for each section were painstakingly derived for each time step. Pile-up effects were estimated using Szebehely’s approach [24] for sections with a large deadrise. Leibowitz went as far as calculating the global deformation of the ship using a beam model and
calculated local stresses in the ship’s structure. The comparison to measured stresses was surprisingly good (figure 5). This enormous manual calculation has not been repeated.

Recently, momentum theory was ‘revived’ by Kapsenberg & Thornhill [25]. The added mass at infinite frequency for a ship using a three-dimensional panel code was calculated, from which they determined spatial added mass derivatives. These added mass derivatives were multiplied by the relative velocity squared to arrive at the impulsive force. It was shown that it is crucial to correct the incoming wave for pile-up effects and for the draft-dependent stationary bow wave. It was demonstrated that accurate predictions are possible (figure 6) also in quartering waves, with a very fast method.

5. Boundary-element methods

Boundary-element methods (BEMs) have been developed for two-dimensional impacts, initially by Greenhow & Lin [26], and later in Norway at the Norwegian University of Science and Technology by Zhao & Faltinsen [27]. BEMs have the advantage of a good solution—within the assumptions made of course—at reasonable computational cost. There is a fundamental numerical problem at the moment of the initial contact owing to the discontinuity of the velocity potential, which causes an infinite pressure. This problem needs some ‘special treatment’ or, as shown by Ogilvie [28], compressibility effects of the fluid should be included.

Just after the initial contact, the fluid close to the body starts to deform. This deformation starts small, also small in relation to the panel size. This means that the disturbance is not accurately modelled, so one has to hope that the...
code rectifies this inaccuracy automatically. As the impact progresses, the fluid surface starts to deform more and more, and a jet can develop. This heavily deforming fluid surface requires a method that continuously checks on the size of the panels in relation to the neighbours and, if required, creates new panels or deletes some panels. Usually the jet is cut away from the solution using the argument that the pressure inside is just atmospheric with the additional benefit that the re-entry problem of the jet is avoided. Even so, the large free-surface deformation requires some tweaking and tuning to get a good panel distribution during the simulation; it will be extremely difficult if not impossible to get this right for all possible impacts. To do this in three dimensions will be even more complicated. If one succeeds in building a stable method, the applicability is restricted to rather academic cases. This is the reason that approximate methods have been developed, the most well known being the one by Zhao et al. [29]. This method has been used for three-dimensional slamming predictions using a strip-theory approach. The first to use this possibility were Kvålsvold et al. [30] in their research on the Estonia accident. Later it was demonstrated by Sames et al. [31] that the choice of the tilt angle of the strips in the bow had a large effect on the resulting impact force. The approach is still used today in an improved method whereby the bowwave system at different drafts is incorporated in the estimation of the wetted surface, as demonstrated in a series of publications by Hermundstad & Moan [32,33] and Tuitman [15].

6. Statistical methods

The statistical method of Ochi [34,35] to predict the probability of bottom slamming is well known. The probability of the fore foot of the ship emerging and the exceedance of a threshold re-entry velocity were combined to calculate the probability of a slam. The probability was evaluated using a Rayleigh distribution, hence linearizing ship motions. Ochi found initially a negligible difference in the threshold velocity for U- and V-shaped vessels, analysing model experiments in regular waves and irregular seas. Later on, Ochi & Motter [36,37] refined the method by introducing slamming coefficients that were dependent on the shape of the lowest 10 per cent (of the draft) of the considered section.

A severe drawback of the method is that the vessel—or essentially the section—is supposed first to fully emerge from the water and then to impact on a flat horizontal surface of the fluid. This is an approximation of bottom slamming; bow flare slamming is not considered. However, the method is easy to use, which made it popular. It also proved to be a valuable tool to compare different ships and, adopting a certain allowable probability of bottom slamming, to determine the maximum sustainable speed in different sea states.

Ochi’s method is applicable to short-term statistics: the statistics of slamming events in a sea state with one particular wave energy spectrum, and with constant speed and heading relative to the waves. To predict the long-term statistics, the statistics of the slamming events that a ship will encounter during its lifetime at sea, is much more problematic. Determining the extreme values itself is complex: maximum impacts occur in a sea state with steep and breaking waves. These breaking waves introduce air bubbles in the upper layer of the sea, which reduce the speed of sound, thereby limiting the maximum speed of the pressure pulse.
This effect will increase the number of slamming events and the severity of the slam. On the other hand, the upper layer is more compressible owing to the air content, which should reduce the maximum peaks.

Next to this, the seamanship of the captain has a very large effect on the long-term distribution of the slamming loads. First of all, the captain will try to avoid the most severe conditions by re-routing. If this action is insufficient, he will reduce speed or change heading; both actions have a very large effect on the severity of the slamming impacts.

7. Analytical methods

In general, analytical methods provide the exact solution for a simplified impact problem. As such, they are used as benchmark tools for approximate methods and also for computational fluid dynamics (CFD) methods. One has to be aware, however, that the analytical solution has no problems in predicting an infinite pressure or an infinite pressure gradient; this will never be possible for a CFD solution with a grid of finite dimensions.

Analytical work started with the previously mentioned paper by Wagner [21]. Potential theory was used to develop a solution for a wedge impacting on a flat water surface. The approximate solution for the free surface was improved upon by Dobrovol’skaya [38], who developed an exact method for impacting wedges, known as the similarity solution. Korobkin [39] also used Wagner’s analysis, and included higher order terms in the Bernoulli equation in order to improve the comparison to experiments. The method was extended to three-dimensional problems by Scolan & Korobkin [40] and Korobkin & Scolan [41]; a solution for axisymmetric bodies or bodies that resemble an axisymmetric body was found. Because the body boundary conditions were imposed on the plane of the free surface, the method can only be used for the initial impact of bodies with a small deadrise angle.

Cointe & Armand [42] studied the problem of an impacting circular cylinder. It was clearly shown that their analytical method was very good for the initial impact problem where the leading parameter \( \frac{Vt}{R} \ll 1 \), in other words, the immersion must be very small compared with the width of the section. This
requirement is illustrated by their estimated free-surface deformation (figure 7). Scolan [43] showed results of impact force calculations and of experiments. The calculated impact force shows the infinitely quick force build-up of the analytical solution while the experimental force build-up is limited by the speed of sound in the fluid (figure 8).

8. Computational fluid dynamics

CFD calculations, by which we mean volumetric methods rather than BEMs, have been applied to impact problems for some 15 years. Arai et al. [44,45] were the first to apply this approach to slamming of ship sections; in those days, this was a simulation of a drop test of a two-dimensional section in calm water. They used an Euler solver and the volume of fluid (VoF) method to determine the free surface. This technique was also used by Germanischer Lloyd [31,46,47]; it was applied in a strip-theory type manner to calculate the impact of pressure on ships in waves. The basic ship motions were calculated using a classical linear three-dimensional BEM.

Work was first done to develop CFD codes that could handle ship motions in waves without considering steep waves and slamming. Problems were encountered with wave propagation into the computational domain and with proper handling of the outgoing waves at the boundaries, and, of course, the large grids required were limited by computer memory. Computer requirements were impressive; together with the memory limitations, this was often a reason not to do grid studies. Moctar et al. [48] presented results of CFD calculations for a large container vessel where both ship motions and impact pressures were calculated. Calculations were done for critical conditions that were identified by a BEM. They showed a good agreement for rigid-body motions, internal loads and local pressure under the bow of the ship. Pressures from the CFD calculation were transferred to a finite-element code for a whipping analysis. We note that the wave condition...
used for the CFD analysis was not a very steep one; it was a condition that produces a maximum vertical bending moment (VBM) in the midship section, a head seas condition with a wavelength of the order of the ship’s length.

Results of calculations for the S-175 container ship were shown by Wilson et al. [49]. His results showed nonlinear force components, but not real slamming events. Kapsenberg & Thornhill [25] showed results for a ferry; the ship was held captive, in agreement with the model experiments. The calculated impact force on a bow element and local pressures agreed very well with the experimental results. On the other hand, they could not successfully calculate the impact force for the steepest waves used in the experiments, but the waves were much shorter than the ship length.

More recently, the method smoothed particle hydrodynamics (SPH) has been applied to impact problems. The method is numerically very robust since it is meshless. Overviews of the features of the method and the developments were given by Monaghan [50–52]. Persisting problems are the interfaces between the fluid and the body, numerical damping, which prohibits accurate wave propagation in large domains, and internal pressure oscillations, which are apparent in local pressures. Despite this, good results have been obtained for the classical dam-break problem [53], problems with two-phase flows like a rising bubble in a fluid [54] and violent wave impacts [55].

All CFD methods are quite computer intensive and need parallelization on a large number of processors to get reasonable performance, but SPH is even worse in this respect. The solver is quite fast since no large matrices need to be inverted, each particle only interacts with its close neighbours, but the time step is very small because, essentially, compressibility is used for time stepping.

9. Structural aspects: hydroelasticity

Already in the early days of research on landing aircraft, the importance of flexible supports for the floats of a plane was realized [20]. A stiff support could easily break at a more violent landing; flexibility in the supporting structure reduces the peak loads in the support structure of the floats. This characteristic is the definition of hydroelasticity: the forces of the fluid on the floats cause the supporting structure to deform; the deformation velocity in its turn changes the fluid loading on the floats.

The problem of hydroelasticity received an impulse from studies on very large floating structures like floating airfields. This work is outside the scope of this review. Relevant here is research carried out in Norway, especially on the loads on flat plates supported by stiffeners. This research was stimulated by a strong development of multi-hulls (surface-effect ships and conventional catamarans) by the local shipyards; the flat plates were a model for the cross structure hitting a wave crest. Kvålsvold & Faltinsen [56] reduced the problem of the plate with stiffeners to that of a flexible beam impacting on a wave crest in two dimensions. The beam was modelled as a Timoshenko beam and this was coupled to a simplified solution (referred to as the outer solution) for the fluid flow in the impact region. Details of the flow at the contact point of the body and the fluid were ignored; it is assumed that this is allowable considering the hydroelastic response of the beam. An analytical solution was found, but the
Figure 9. Force on a beam when impacting on a wave crest. The top line represents the force on the fully rigid beam; the full line shows the very large reduction of this force due to the flexible response of the beam [56]. Solid line, total force; dotted line, local excitation force; short-dashed line, damping force; long-dashed line, inertial force.

Figure 10. Strain as a function of the non-dimensional ratio of the duration of the impulse and the natural period of the structure. Results from calculations of a stiffened plate field Faltinsen [7]. Results of calculations at different non-dimensional impact velocities (crosses, open circles, triangles and squares), quasi-steady orthotropic plate theory (dashed line) and hydroelastic beam theory (solid line).

work on numerical solutions (BEMs) failed for stability and convergence reasons. Since the analysis is linear, a decomposition of the different force components can easily be made; the results in figure 9 show that the effect of the elasticity of the beam on the hydrodynamic force is quite dramatic. This work was extended by Haugen & Faltinsen [57] using orthotropic plate theory and applied to a physical model consisting of three segments by Ge et al. [58].

Hydroelastic effects are only relevant for local impacts when the relative angle between the body and the surface of the fluid is small, and if the duration of the impact is short relative to the resonance period of the structure. This is expressed by Faltinsen [59] by a parameter that we identify here as Faltinsen’s slamming parameter: FSP = \( \tan \beta / \sqrt{\rho L^3 / EI} \). FSP is proportional to the ratio of the wetting time of the beam and to its lowest natural frequency. Using the results of calculations on a wedge built from a stiffened plate, a diagram was drawn showing the effect of hydroelasticity on the strain (figure 10). This figure

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Figure 11. Hydroelastic and air inclusion effects on the maximum displacement of different two-dimensional wedges characterized by the deadrise angle (first horizontal axis). The structural properties are characterized by the first dry natural frequency (second horizontal axis). Adapted from Bereznitski [60].

shows a full elastic response for FSP < 0.25 where the stresses are proportional to the impact velocity, a transition area for 0.25 < FSP < 1.50 and a quasi-static response for higher values of the parameter where the stresses are proportional to the impact velocity squared.

Bereznitski [60] essentially studied the same problem of a two-dimensional wedge entry where the wedge consisted of a beam with finite stiffness. By calculating a series of wedge shapes with a deadrise angle of 0°, 2°, 5° and 10° and, for each case, four different values of the stiffness of the beam, figure 11 was constructed. This figure shows that neglecting hydroelastic effects can, in the extreme case, result in an overprediction of the displacement (and hence the stress) by a factor of 10. Note that this is for a very extreme case; a flat impact on a very flexible structure.

10. Experimental techniques

A slamming experiment is not an easy experiment; this was well detailed by Lewis et al. [61]. The duration of the impact is usually short, especially if local quantities, like the pressure, are of interest. This means that high sampling rates like 5–10 kHz are required; for a flat impact even higher sampling rates are necessary. In addition to the requirements for the measurement system and the data acquisition system, there is the problem of the sensor itself. Nowadays, there are piezo-electric pressure sensors with very high natural frequencies. It must be realized that the quoted high frequency is the frequency in air; the natural frequency submerged in water is much lower. Much work was done in
the 1960s and 1970s to capture the peak of the local pressure pulse; these results were no doubt affected by the accuracy and the maximum sampling rate of the measurement systems of those days.

Systematic experiments were carried out on two-dimensional bodies like wedges as early as 1952 by Bisplinghoff & Doherty and are still being done recently [61–63]. Bisplinghoff & Doherty [64] carried out free-fall experiments and derived the impact force from the deceleration of the test section. The wetted length of the wedge during the impact was studied using a high-speed film camera that was able to shoot 1500 frames per second. Their results for the $10^\circ$ wedge did not agree with the existing theories of Wagner [21] and Mayo [65]; the results for the $20^\circ$ and $30^\circ$ wedge showed a better agreement.

Tveitnes et al. [62] carried out more sophisticated tests on wedges using an apparatus that imposed a constant velocity during water entry. Tests were carried out for wedges having a deadrise angle ranging from $5^\circ$ to $45^\circ$. All sections had the same width; the models had a hard chine at the maximum width and vertical walls. They measured the total force on the section for various water entry velocities and also for some water exit cases. Their results from the water entry tests showed significant dynamic effects that were attributed to the different components of the test apparatus, illustrating the complexity of the experiment. De Backer et al. [63] carried out drop tests with a hemisphere and cones with different relatively high deadrise angles. A high-speed camera was used to measure the impact velocity and the pile-up along the body. Measured pressures on the bodies were significantly lower than predicted by asymptotic theory, especially those of the cones. Regarding the relatively large deadrise angles of the cone, this is not surprising. Lewis et al. [61] carried out drop tests with a two-dimensional wedge. A high-speed camera was also used to measure the position of the wedge and it was found to be more accurate than a traditional position gauge and double-integrated acceleration signals. Lewis et al. detail an extensive uncertainty analysis, again showing that attention to detail is required for accurate measurements.

Research on hydroelastic effects initiated a series of experiments used for validation of the developed theory. Work was done in Norway by Kvålsvold & Faltinsen [66] on a flat plate supported by stiffeners dropping on a wave crest; similar tests were carried out by Samuelides & Katsaounis [67] and Vredeveldt et al. [68]. Results of this work showed that the lower deformation modes had a dominant effect on the maximum strain. The slamming peaks can be very high, but with a very short duration.

Experiments carried out by Shibue et al. [69] with a steel cylinder and by Arai & Miyauchi [70] with a thin-walled aluminium cylinder showed large differences in the deceleration (owing to the difference in mass) and in the stresses, owing to the deformation of the aluminium model. A fully coupled hydrostructural approach is necessary to predict stress levels in such a flexible structure. Such an analysis was performed by Ionina & Korobkin [71]; a good agreement with Shibue’s results was shown.

Kvålsvold & Faltinsen [66] presented the results of drop tests with a flat plate on a wave crest. The results were compared with a two-dimensional theory using a beam model for the plate and a nonlinear BEM developed by Zhao & Faltinsen [27]. The displacement is shown in figure 12; the agreement for the initial displacement is very good, but there is a marked change in the natural frequency
of the plate after the initial deflection, $t > 0.008$ s. Faltinsen [6] attributes this to ventilation or cavitation, which causes the plate to vibrate in the dry natural frequency. This seems logical considering the negative pressure that has been measured (figure 13). The good agreement between the predicted and measured initial displacement while the initial peak in the pressure was fully absent in the theoretical result (figure 13) illustrates that a high, short-duration, pressure peak has little consequence for the deformation.
Experiments with complete models of ships are carried out to measure the global response. Basically, there are two ways to do this, to build a completely elastic model or to divide the model into a number of segments and to connect them with an elastic beam. The first approach can be quite expensive if one attempts to model an existing ship in detail. For research purposes, a much simpler model can be built from some elastic material. This last method was used by Watanabe et al. [72] for experiments on the S-175 container ship and by Hay et al. [73] for experiments on a frigate. Some problems were indicated by the last group of authors regarding the effect of installing components like the electrical motor and drive train needed for propulsion on the elastic properties of the model. The approach of using a fully elastic model was reviewed by Iijima et al. [74]. They concluded that it was unavoidable to use some plastic as material for the elastic model; this material has a lot more internal damping than the steel or aluminium prototype, thereby affecting the elastic response of the model. This aspect is especially important for successive slamming; the phasing of the second slam with the still-active whipping response of the model has an enormous effect on the dynamic response of the second impact, as shown by Kapsenberg et al. [75].

Most experiments on complete models of ships are carried out using segmented models. There are two methods for designing the beam for such models: the first is to build a beam with a very stiff main part and flexible connections and the second is to build a continuously bending beam. Examples of the first method are in the experiments carried out by Hermundstad et al. [76], Lavroff et al. [77] and Drummen et al. [78]. Examples of the second method are the experiments by McTaggart et al. [79], Dessi et al. [80] and Iijima et al. [74]. The advantage of the first method is that the flexible connection can be made adjustable, while adjusting the beam is more complicated. However, both methods appear to give good results in comparison with calculation methods.

11. Full-scale measurements

There are quite a few full-scale experiments on slamming reported in the open literature. In general, this type of measurement needs a complicated set of instruments and measurement system, and, if you are looking for it, bad weather is not always easy to find. For commercial ships sailing fixed routes, this means that a measurement campaign needs to cover several years in order to have a decent chance of success.

The earliest documented full-scale seakeeping trials were those on Dutch destroyers reported by Warnsinck & Saint Denis [81]. The instrumentation was self-made and consisted mainly of stress measurements. The main problem was the lack of information on the sea state. This problem was avoided in later trials by doing side-by-side tests [82]. These measurements were analysed by Leibowitz [22] who applied momentum theory to compare theoretical results with the values measured at full scale, as mentioned previously.

The Ship Structure Committee ordered an extensive study in the 1960s. This study started by developing an automated measurement and recording system for full-scale internal load measurements [83]. This system was later used for several campaigns on cargo ships [84]. One of these ships, SS Wolverine State
(figure 14) was further instrumented with pressure gauges to measure slamming pressures in the bottom. It is interesting to note that this ship type experienced damage to the bottom plating on earlier occasions. Results of the slamming measurements were reported by Wheaton et al. [85]. Measurements took place over a 3 year period; during all this period, significant slamming occurred only on three west-bound trans-Atlantic voyages. No measurements were carried out on the environmental conditions; also the wind speed was estimated by the crew of the ship. The conclusions from this project are therefore rather general. The Poisson distribution as predicted by Ochi [34] for the time interval between slams was confirmed. The head seas condition was the most severe one considering the number of slams. An effort was also made to estimate the relative velocity at the moment of the impact; this was done on the basis of the signal of the pressure gauge with considerable simplifications. Accepting the high uncertainties of this procedure, a relation was found between impact velocity and peak pressure that was close to Ochi’s [34] value from model experiments using a Mariner hull form, but peak pressures were a factor of four lower than Chuang’s [86] results from drop tests.

Aertssen [10,87] carried out measurements on many ships. From these measurements, performance diagrams were created, as illustrated in figure 15. These diagrams show basically the speed of the ship as a function of the weather conditions—expressed as a Beaufort number—at various power levels, but they also show some limiting seakeeping parameters like the number of slams and the number of propeller emergences per hour, bow acceleration and probability of deck wetness. The weather conditions were based on observations by the crew, and the actual wave spectrum is only characterized by a Beaufort number.

Andrew & Lloyd [88] carried out side-by-side trials on two frigates of the Royal Navy. They used wave buoys to measure the sea state; later on, their results were used by Bishop et al. [89] to validate their unified dynamic theory of a flexible ship hull with good results. One interesting conclusion from their work was that different methods to estimate the slamming forces gave a wide spread of the distribution of the peaks of the VBM amidships (figure 16).

Aalberts & Nieuwenhuijs [91] focused on the contribution of the whipping component on the VBM onboard the 124m general cargo/container vessel Victoriaborg (figure 17). They did not measure the sea state, instead they used an automated measuring system that collected data over a full year and from this they considered statistical distributions of the peak values. It was concluded for
Figure 15. Performance diagram of cargo liner *Jordaens*. Adapted from Aertssen [10]. Diagram shows lines for different power settings (solid lines), maximum significant wave stress and maximum whipping stress (dotted lines), significant pitch angle (dashed line), probability of propeller emergence (PE; dashed-dotted line), probability of slamming (S; light dotted line).

Figure 16. Distribution of the peaks of the VBM for different estimators of the slamming force [89]. Estimations using the method of Leibowitz [22] (open squares), Stavovy–Chuang [90] (open circles), Ochi–Motter [37] (open triangles) and measurements (crosses).

this hull form with very little bow flare that the whipping component contributed significantly to the fatigue damage: the number of cycles increased by 35 per cent and the extreme value by some 15 per cent.
More recent projects that have been carried out often remain unpublished for confidentiality reasons. Within the Cooperative Research Ships, administrated by the Maritime Research Institute Netherlands (MARIN), several long-term monitoring campaigns have been and still are being carried out. A recent development is to use the backscatter of the navigation radar to estimate the three-dimensional wave spectrum [92]. Several such systems are available on the market and, after tuning, these systems give a good estimate of the sea state. The main uncertainty is the estimate of the wave height. This measurement is heavily affected by the presence of very small wavelets on top of the wave owing to a local wind field.

It has been proposed by Thornhill & Stredulinsky [93] to combine the measurement from the wave radar with measurements of the ship motions. Using pre-calculated ship motions and the measured wave spectrum, one can determine a correction factor for the spectral value for each frequency and wave direction bin, thus correcting the significant wave height.

12. So, where are we now?

It is clear that an enormous amount of work has been done and that impressive results have been obtained, but it is still insufficient to advise the industry on the suitability of a particular ship design on a certain route. The questions posed in the first section on the acceptability of a certain bow flare in a particular sea state can still not be answered.

Developments in the last decades have shown that ships are getting bigger and hence are more flexible than ever before. The use of high-tensile steel allows a reduction of the structural dimensions (in comparison to normal steel), which again makes the structure more flexible. This development increases the need to determine the stresses owing to the flexural deformations of the ship’s hull. The reason to include this is twofold: the effect of the flexural deformations on the extreme wave-bending moment—hence the design value—and the effect on fatigue aspects.
Calculating the dynamic response of the ship’s girder on a given dynamic load using a structural model seems a solved problem. The introduction of deformation modes into hydrodynamic calculations was developed by Bishop & Price [94] and has basically remained unchanged. The main problem, however, resides in the calculation of the excitation for the different deformation modes, as was clearly demonstrated by Bishop et al. [89]. It is a pity that an enormous amount of work has been devoted to a proper measurement and prediction of the peak value of the impact pressure. For many purposes, this value has no consequences since the duration of the peak is very short, therefore, it contains very little impulse. The global response of the ship owing to a wave impact is determined by the spatial integral of the pressure pulse as it travels over the hull. Although the peak pressure might be high and the high-pressure area might be narrow—resulting locally in a high pressure of short duration—the hull girder is excited with a force of relatively long duration owing to the relatively low speed at which this pressure pulse travels over the hull. The short-duration slamming peak is only important for very special applications like the containment systems for liquefied natural gas owing to the special structure of flexible panels and very stiff supports.

Analytical methods to predict slamming impacts have a limited usefulness. Often they can only be applied to simplified shapes and are limited to just the initial stage of the impact. BEMs are rather more flexible, certainly with respect to the hull form, but the large surface deformations cause enormous problems for a proper and accurate evaluation. This is the reason for the popularity of the approximate BEMs.

The future of numerical predictions is certainly in CFD. The combination of steep and large waves with a ship at speed is essential for a correct solution of the slamming problem. It is recognized that viscous and boundary-layer effects are not important for slamming, but the full interaction of the incoming wave with the moving ship’s hull needs to be solved. CFD does not have the elegance or the efficiency of the more traditional methods, but the power and memory capability of modern multi-processor computer systems make simulations of three-dimensional cases possible, although it still takes days for a simulation of limited duration (a few wave encounters). The importance of predicting the pressure pulse correctly requires small cells in the impact zone; this makes the problem larger (with respect to memory requirements) than the normal problem (without slamming) of a ship sailing in waves. Whether the future is brighter for the ‘normal’ CFD methods or for SPH is difficult to predict. SPH is numerically a very robust method and impressive results are obtained for very violent phenomena. However, work on verification of the results (convergence with respect to particle size and time step) is not yet at the level of the normal CFD. For the moment, the main problems with SPH are wave propagation in a domain and a robust treatment of the body–fluid interface, while computer requirements are an order higher than for normal CFD methods.

Full-scale measurements are becoming more useful in slamming research. Early measurement campaigns illustrated and quantified the seriousness of the slamming phenomenon, but these data could not be used to validate computational methods; only recently an accurate measurement of the actual wave condition has been possible. Long-term measurements of one ship to determine extreme values are not very useful, not even if they last over the complete lifetime of the vessel. Serious slamming does not occur often and ship
operators try to avoid these conditions whenever possible. Monitoring campaigns of large container ships have shown that they do not encounter slamming conditions every year. Validation is only possible for the one occasion that the ship encounters these conditions. Modern developments using wave radar [92] show great promise. The estimation of the wave height is still the weak point; this needs continuous tuning by an expert or it can be calibrated by the measured ship motions [93], which is the course of current developments.

One of the objectives of all these developments is to have proper structural requirements in the rules that include the effects of impulsive loads and dynamic responses. Classification societies are working hard to include this in the prediction of ultimate and fatigue loads, but they are not yet there, as was demonstrated by the research carried out after the Napoli accident. Pedersen & Jensen [95] have worked already on very general formulas to quantify dynamic effects in a form suitable for rules, but this seems rather premature since the method used is not yet thoroughly validated.

13. Remaining challenges

It is believed that we are close to numerically solving the whipping problem for ships. A pragmatic method to achieve this capability has been proposed by Kapsenberg & Thornhill [25], who presented a tunable approximate method for the impulsive load caused by slamming that can be included in long-term simulation software. However, they still have to demonstrate that this objective was achieved. It might very well be that the way the waves are generated for these predictions, by way of superposition of harmonic components, is insufficient to correctly predict the right amount of steep waves that are so important for the large slamming impacts. It might be necessary to use a higher order wave description to arrive at a proper estimation of the slamming loads. When this is realized, the problem of modelling the seamanship of the captain remains a crucial component for a realistic long-term distribution of the bending moments.

Predicting the local response is far more complicated because then a detailed pressure distribution is required. Phenomena like air inclusions, hydroelastic response of the structure and compressibility effects of the fluid are important for impacts where the surface of the fluid is close to parallel to the body. Predicting full-scale values from scaled experiments is quite complex. Scaling laws for impacts with a significant amount of trapped air still need to be developed. Describing the phenomena, as done by Lugni et al. [96] and Bogaert et al. [18], is a first step towards this goal. Possibly, the final solution is a CFD method where all relevant physical parameters are properly modelled so that separate calculations for the model and full scale can be made. This is then analogous to the prediction of the wake field of a ship: separate CFD calculations are being done for the model and at full scale.

Full-scale measurements are always necessary. Not only is this the only real environment for which the (ship) design is ultimately intended, but real-life details can have an important effect on impact phenomena. One of these real-life details is the volume fraction of air bubbles in the upper layer of the sea, especially during weather conditions where there is high probability of slams: an increasing wind with a rising sea state with steep waves. A good validation for
slamming calculations would be a deterministic slamming event at full scale. This means that the impact condition, the actual wave surface in space and time, the pressures on the hull in the impact area and the hull dynamic response need to be fully recorded. For a small boat, such a deterministic event could be possible by creating a steep wave with one ship and running at high speed through the wake with the second instrumented ship. Alternatively, one could create a measurement range where the surface is covered by radar to measure the spatial/temporal wave elevation, but then one is dependent on the proper weather conditions.

For large ships, this does not seem feasible; a short-term statistical approach is then the only alternative. The ship should be instrumented with a radar system to measure the wave environment, accelerometers to quantify the whipping response, a strain gauge system to measure the global loads at different sections and strain gauges to measure local stresses in the impact area. It is difficult to get permission to install pressure gauges; ship owners and Class societies are not too enthusiastic about drilling holes in the hull and, unfortunately, quite a few gauges are required in order not to miss the interesting high-pressure area. Full-scale measurements are essential to check the statistical distribution of slamming-induced loads. For the short-term statistics, this is a check on the proper evaluation of all physical details; for the long-term statistics, this is mainly a check on the model of the captain applying prudent seamanship.

14. Conclusions

Published literature on ship slamming in waves has been reviewed with an eye on the practical application of the proposed theories and the usefulness of experiments carried out, on the problem of real ships sailing at sea. The problem of ship slamming can be subdivided into a local problem of a small part of the ship’s structure, which is actually hit by an impulsive load, and the problem of the global response of the ship structure, referred to as whipping.

The local problem is quite complicated, certainly if the angle between the impacting fluid surface and the structure is small. Unfortunately, this is the condition in which the impulsive forces are highest. If this relative impact angle is small, effects like air inclusions, local air bubbles present in the fluid, compressibility effects and details in the inflow conditions play a role. If the structure is flexible and starts vibrating, local cavitation might also occur. With a great deal of effort, these effects might be included in model experiments, but extrapolating such results to full scale is, as yet, a challenge unsolved. It is suggested that only a computational method including all these effects will be able to accurately predict such phenomena.

The situation is brighter for the global problem. Local effects are filtered because the integrated pressure in space is relevant as an exciting mechanism. Recent developments have shown that CFD methods are now able to calculate the impulsive force on the ship’s hull, although such calculations in really steep waves have not yet been published. It has been suggested that a two-stage approach might be useful for this problem: a CFD-based method to calculate the impulsive force owing to individual waves in specified conditions and an approximate method, tuned on the CFD results, to be included in long-term simulation programmes. However, a realistic long-term distribution of the bending
moments of a ship is, apart from the hydrodynamics, also quite dependent on the actual way the ship is being used. The amount of weather routing, speed reduction and course changes to avoid heavy slamming will have a dominant effect on the extreme loads; research on this aspect is still in its infancy.

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