SUMMARY

Comfort and reliability were important targets in the design of the Queen Mary 2. These performance aspects were checked early in the development of the ship. In the first stage of this work theoretical calculations and model tests were performed to quantify the basic motion characteristics and added resistance. In the second stage this information was combined with a climate description for anticipated routes, criteria for tolerable ship behaviour and a scenario for the reaction of the master on the encountered circumstances. The results of these scenario simulations, in which many individual voyages were mimicked in detail, were used to investigate the impact of various sailing strategies on passenger comfort, fuel consumption and service reliability.

The paper highlights the owner’s requirements regarding comfort and reliability, the basics of the techniques that were used to ensure adequate performance, key results of the project and the present experience with the vessel.

1 INTRODUCTION

The Queen Mary 2 is quite a remarkable ship. The withdrawal of Cunard’s venerable 80,000 grt Queens, Mary (1936) and Elizabeth (1940), by late 1968 was only partially offset with the introduction of the 65,000 grt Queen Elizabeth 2 in 1969. Many suggested that once the new Queen had seen out her lifespan the age of the transatlantic liner would finally come to an end. Certainly the cost differential between building and operating a true liner compared to a cruise ship was identified as a major obstacle for any future transatlantic project. This could only be overcome if there was an overwhelming demand for the continuation of the Atlantic ferry.

The differences between the liner and cruise ship can be described as fundamental:

- The liner generally is higher powered and in consequence generally has a higher speed potential compared to the cruise ship
- The liner generally has a deeper draught compared to the cruise ship
- The liner generally has a higher deadweight capacity compared to the cruise ship
- The liner generally has greater strength compared to the cruise ship
- The liner generally has a finer form compared to the cruise ship

When Cunard Line was acquired by Carnival Corporation in May 1998 the new management immediately assessed the options for expanding the brand. Cunard Line’s most famous and profitable ship was the Queen Elizabeth 2. A life extension refit in 1987 had seen the replacement of her outmoded steam turbine propulsion plant with a modern diesel-electric installation. The ship continued to offer a mixture of traditional six day transatlantic crossings between Southampton and New York (and back), interspersed with cruises. After the 1997 Titanic motion picture, cruising, particularly transatlantic crossings, had seen an upsurge in popularity. The financial implications of building a new liner, as opposed to a cruise ship, to replace the QE2 were considered. Eventually it was decided that if a large optimised ship could be developed, maximising ticket and on board revenue potential to offset the costs associated with the liner, the project could be a viable proposition. From this premise Queen Mary 2 was designed and built.

The most important attribute that the new ship had to possess was reliability with regards to her schedule. On the classic six day transatlantic run the ship would leave her home port of Southampton at 6.00 pm on day one. On day six she would arrive at New York at 6.30 am. After a ten hour turn around where her original passengers and their luggage would disembark, the ship would re-provision and refuel and with the return passengers and luggage embarked, she would return to Southampton. Any delays brought about by inclement weather en route between Southampton and New York would reduce the tight ten hour turn around. In the extreme the ship might be very late for her next departure to the point where she could not make up the lost time, resulting in the travel plans of thousands of passengers being disrupted, not only for the immediate voyage but the knock on across the season. This would result in huge cost penalties from refunds and rescheduling of flights and hotel bookings.

In order to define the ship’s contract with regards to speed and power an estimate had to be prepared as to what maximum speed would be required to ensure that the ship would be able to maintain her schedule in all anticipated weather conditions. After analysis of data from QE2 it was decided to adopt a maximum speed of 29.5 knots provided by four Mermaid propulsion pods rated at 21.5 MW each. Following the signature of the
contract and the appointment of MARIN to perform the hydrodynamic model testing for powering, seakeeping and manoeuvring, MARIN offered to perform a significantly enhanced routing and scheduling analysis of the transatlantic crossing. This paper describes the work that was done.

2 SEAKEEPING ISSUES IN THE DESIGN

2.1 COMFORT

The main quantitative comfort indicators that were used to evaluate the comfort performance of the ship were the concept of the “Motion Induced Interruption” (MII, an event in which a standing person will look for support), “Motion Sickness Incidence” (MSI, Colwell 1989) and the “Maximum Transient Vibration Value (MTVV).

The MII [Graham, 1990] is determined by a combination of vertical and transverse accelerations. It is expressed in the hourly number of events.

Although more recent work [Dallinga, 2002, Bos, 2002] has made us aware that lateral motions and roll can contribute significantly to the MSI levels, the present work limited itself to the effects of the vertical accelerations.

![Fig. 1: MSI as a function of acceleration level and period](image)

The MTVV [Griffin, 1990] was used as a measure for discomfort due to the slamming induced transient vibrations. In the present case only aft-body slamming was considered.

2.2 SAFETY

Safety issues that were considered from the outset were extreme roll angles in steep waves from the stern quarter, extreme roll angles due to parametric roll, shipping green water on the fore deck and hull girder vibrations due to excessive bow flare slamming.

3 STARTING POINT FOR THE DESIGN

- Cunard’s considerations, based on experience with the QE2
- Carnival Corporate Shipbuilding design criteria
- Chantier’s considerations based on modern shipbuilding practice and budget constraints

The starting point for the design in May 1998 was an evaluation of the Queen Elizabeth 2. She was by that time the last ship employed on the transatlantic passenger trade and had been transversing the Atlantic for over 30 years. In fact she had crossed more times than the former Queen Mary and Queen Elizabeth combined.

Elements of the ship’s original design that were considered successful and that had stood the test of time were noted, whereas areas where improvements were thought possible were carefully considered. An early decision was to abandon a new ship design of Panamax dimensions. Although QE2 was built to transverse the canal she only utilises this embodiment once a year on her World Cruises. The economics of the project dictated that the new ship should be as large as possible to take advantage of the “economy of scale” effect and it was therefore decided to design post Panamax to the largest dimensions possible commensurate with operating her into Southampton and New York. Length was constrained by the turning basin at Southampton and the length of the finger piers at New York that jut out into the Hudson River, height was limited by the requirement to transverse below the Verazzano Narrows bridge at the entrance to New York and draught by the depth of water at the two ports. In keeping with the true liner concept a fine bow, low block coefficient form was judged to be desirable. Since the bow form of QE2 had proven itself to be eminently suitable for Atlantic service, the bow of the new ship was modelled on this, although considerably enlarged because of the greater size of the new ship.

Pertinent design elements from other North Atlantic liners, such as enclosing the forward part of the wrap around promenade of the Boat Deck, were introduced into the new ship where appropriate. Modern day storing techniques, garbage disposal and messing arrangements were incorporated from lessons learnt with the cruise industry. The only proviso in dictating whether a new idea was used in the new ship was that the transatlantic liner form of the vessel, in respect to her physical and operating characteristics, was deemed paramount and had to be maintained.
4 DESIGN VERIFICATION

4.1 INTRODUCTION

To assure the performance of the vessel, work was carried out in three stages. These comprised:

- initial calculations;
- model tests;
- scenario simulations.

The fact that some elements of seakeeping are accessible by numerical means was exploited to obtain an early assessment on the suitability of the design. The issues addressed were the added resistance, comfort in relation to vertical acceleration and the performance of the fin stabilizers.

Model tests served a dual purpose. First they were used to quantify those aspects that were hard to calculate, like bow flare slamming in waves from a forward direction, stern slamming in following seas and course keeping in waves from the stern quarter. Secondly they provided an open minded, independent check on the behaviour of the design.

Because the behaviour alone in discrete conditions does not give much insight into operational performance, the foregoing results were combined with an operational scenario (with the criteria set for tolerable ship behaviour) and a detailed description of the anticipated wind and wave climate and used in scenario simulations. In these simulations a total number of about 900 crossings (east- and west-bound) were used to judge the operational reliability.

4.2 QUANTIFICATION TECHNIQUES

Calculations

The theoretical calculations were performed with a conventional strip theory code and a 3D panel code. The latter provided the information on the local flow velocities around the bilges that plays an important role in the assessment of the stabilizer performance.

Model tests

In order to obtain an independent and complete impression of the ship’s behaviour, model tests were performed with a free running model in irregular waves. The model as with the actual ship was steered using the aft azimuthing POD units, which were controlled by means of an autopilot. The helm angles were governed by the offset from the desired track in the basin, the course deviation and the rate of turn. A simple PD controller was used.

Fig. 3: Seakeeping Model.

Active fin stabilizers were mounted on the model to obtain a realistic impression of the ship’s behaviour. Their mechanical reaction was governed by the roll and roll velocity of the ship.

Figure 4: Model of the Queen Mary 2 in Extreme Waves

To quantify aft body slamming two possible approaches can be used. The first is to measure the impact pressures in detail and to apply the resulting impulsive excitation in an FE model of the ship to obtain the transient vibrations. The second approach is to model the flexibility of the ship in the model and to measure the flexural response of the hull directly.

A problem with the first approach is that the excitation area has to be known; an advantage is that, by using a detailed FE model, all relevant flexural mode shapes are accounted for. A problem of the second approach is the limited possibilities to model the mode shapes. An advantage is that one obtains direct results. For stern slamming both approaches yield similar results.
[Kapsenberg, 2003]. In the present case the first approach was adopted. The set-up of the pressure gauges is shown in Fig. 5.

Fig. 5: Pressure gauge set-up.

**Scenario simulations**
The behaviour in particular combinations of speed, heading and wave conditions is not a direct measure for the operational performance. The persistence of weather systems, the reaction of the master on the encountered ship behaviour and the wind and wave climatology are important parameters as well. Contemporary techniques for scenario simulations [Aalbers, 2001, Dallinga, 2004] facilitate a detailed assessment of the operational reliability that accounts for all of these aspects of the problem.

![Scenario simulations diagram](image)

Figure 6: Schematic Representation of Operational Scenario
In scenario simulations, a large number of individual voyages are mimicked in a step-wise simulation. The use of (historical) hind cast data (in this case from the atmospheric and wind wave models of the European Centre for Medium Range Weather Forecasts ECMWF) as input for wind and waves solves the problem of accounting for the right coherence between wind and waves, their persistence and the varying spectral characteristics of the waves.

![Simulated Routes](image)

Figure 7: Simulated Routes

![Wind speed and direction](image)

Figure 8: Wind speed and direction on the north Atlantic on Jan 10 1999 as accounted for in the simulations

4.3 HYDRODYNAMIC CHARACTERISTICS

**Ship Behaviour**
Regarding the ship behaviour the basic work quantified the “rigid body” motions and related acceleration levels.

**Pitch Response in Irregular Waves**

![Pitch Response](image)

Fig. 9: Pitch Response vs. Heading
**Pitching**
The pitch response of the Queen Mary 2 in irregular waves is shown in Fig. 9. It illustrates the fact that for a vessel of her size, head seas do not represent the most severe case from the point of view of pitching; quartering wave directions yield a higher response.

**Vertical Accelerations**
Because the roll response is typically small in waves from forward direction, the heave and the pitch response are the prime drivers for the vertical accelerations.

**Roll**
In the calculations the effect of the fin stabilizers on the roll response was estimated by means of a formulation that was developed in the Motion Control working group of the Cooperative Research Ships. The results were used to select appropriate control gains for the servo’s that controlled the fin angle on the hip model. Figure 10 shows the effect on the roll; the effect of the stabilizers is largest in the resonant roll cases in waves from the stern quarter.

**Added Resistance**
The initial estimates on the added resistance in waves are based on the Gerritsma-Beukelman method [Gerritsma, 1972] that accounts on the energy dissipated by the heave and pitch damping. Known shortcomings of this method are the added resistance in short waves (where reflections are the main source of added resistance), the increase of the added resistance due to bow flare immersion, the contributions of yawing, course keeping and steering in waves from the stern quarter and the results at low speeds. The scenario simulations ask for an estimate of the added resistance for every forthcoming combination of ship speed, wave direction and wave condition. The problems with the robustness of the calculation methods were overcome to some extent by adopting a generalized version of the empirical formulation of Jinkine and Ferdinande [Jinkine, 1974] in the assessment of the sustained speed.

**Mean and Extreme Fuel Consumption**
An interesting result of the analysis of the fuel consumption is the fact that the mean increase due to “weather” is rather small (around 5%). That does not mean that the added resistance from wind and waves is always small; in many storm conditions the total of wind and waves reaches up to 30-50% of the total resistance.
The operational scenario clearly influences the fuel consumption. In particular the comfort scenario, where the delays due to a temporary speed reduction are recovered in later parts of the trip, shows incidental high values.

The above results are reflected in the variation in engine use. The efforts to arrive in time in the just-in-time and in particular in the comfort scenario require occasional high engine power.

![Engine Use](image1)

**Comfort**

The fact that the stabilizers are very effective led to the situation that discomfort in terms of impaired passenger mobility (quantified in terms of the frequency of motion induced interruptions MII) was hardly an issue. Because of this, seasickness due to vertical accelerations (quantified in terms of the “motion sickness incidence” MSI) became the most important comfort indicator.

Assuming that seasickness is a fairly “traumatic” event that one does not forget easily, the analysis of the results of the simulations focussed on the maximum MSI levels per trip.

![Fraction of Trips Exceeding 10% and 20% MSI](image2)

**Reliability**

The foregoing it can be concluded that for a cruise liner it is not the over-all increase in resistance that governs the required service margin. Instead, it is governed by the incidental character of adverse weather, in combination with the requirement for a reliable service that requires the incidental use of relatively high engine power.

The results in Fig. 15 indicate the relation between the available power and the risk of an unacceptable delay. A scenario in which comfort is maintained, increases the power requirements.

![The Risk of Delay vs. Engine Power](image3)

### Operational Experience

The Queen Mary 2 has now been in operation since January 2004. Considering the available experience to date it can be concluded that the ship is an exceptionally good sea boat offering a high degree of comfort. Regular Cunard transatlantic passengers and experienced crew members have described the ship as offering superior performance in adverse weather. This is undoubtedly a function of the ship’s size and by virtue that she has been designed as a true transatlantic liner with all the necessary attributes such as fine form, deep draught, great structural strength and reserves of power. During her first transatlantic season the ship maintained her rigid schedule without undue difficulty as predicted by the simulation scenarios.

### Conclusions

In a seakeeping and performance assessment some areas are accessible by means of quantitative methods; these methods allow a careful optimisation of a design. Other areas can only be dealt in qualitative terms, in which case sheer conservatism reigns. Considering the present operational experience with the Queen Mary 2, the design of which is based on a mix of both approaches it seems justified to conclude that:

- the work yielded an adequate assessment of the sustained speed and comfort of the design;
- the service margin is adequate to obtain a reliable service on a north Atlantic route.

The above does not mean that future designs can not be improved. These opportunities require:

- a careful check on the criteria that were adopted for tolerable ship behaviour (in a qualitative and quantitative sense, to be achieved by monitoring passenger comfort and the masters reaction on circumstances);
• a quantitative approach in the assessment of the impact of slamming at the bow on comfort and performance.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

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