Debut of First Large Passenger Cruise Ship Built in Japan for Princess Cruises

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The passenger cruise ships "Diamond Princess" and "Sapphire Princess" were completed and delivered to the owner, Princess Cruises, on 26 February and 27 May 2004, respectively, at the Nagasaki Shipyard and Machinery Works of Mitsubishi Heavy Industries, Ltd. (MHI). These ships are a new generation of large passenger ships that will sail as the Grand-series of advanced vessels by Princess Cruises, part of the Carnival Group. New concepts are incorporated in the designs of the ships in which environmentally friendly power generation, propulsion, and waste treatment systems using advanced technologies have been installed onboard. Both sister ships are now in service along the west coasts of the U.S. and Mexico.

1. Introduction

The "Diamond Princess" and "Sapphire Princess" (**Fig.1**) are large luxury passenger ships with a gross weight of approximately 116 000 tons each. They are the first ships of their type to have been ordered and constructed in Japan for a leading overseas cruise company.

This report presents an outline of the ships and reviews some of the technical challenges and features of the design and construction of these large passenger ships. These challenges and features include measures for environmental protection, measures against smoke emissions, efforts to reduce vibration and noise, and an outline of the recovery work undertaken for the ships after the occurrence of a fire accident during the construction of the first ship on 1 October 2002.

Fig. 1 Overall view of ships
Sister ships cruising off Victoria, Canada; Left: Sapphire Princess, Right: Diamond Princess.

2. Outline of the ships

The major specifications of both ships are shown in **Table 1**, and a view of the general arrangement of the passenger accommodation spaces is shown in **Fig. 2**.

2.1 Passenger cabins

Some 72% of the total 1 339 passenger cabins onboard are outside cabins that face the sea. In addition, 78% of these cabins have their own private balcony. Moreover, a total of 29 passenger cabins are equipped with facilities that can accommodate handicapped persons, such as passengers restricted to wheelchairs.

Table 1 Major specifications of the ship

Classification		Lloyd's Register of Shipping
Gross tonnage		App. 116000 GT
Overall length	(m)	App. 290
Length b.p.	(m)	246.0
Breadth (moulded)	(m)	37.5
Height above sea level	(m)	54.0
Design draft	(m)	8.05
Service speed	(kt)	22.1
Main power generating engines		
Diesel engine	(kW)	2 X 9 450 2 X 8 400
Gas turbine	(kW)	1 X 25 000
Propulsion motors	(kW)	2 X 20 000
Number of propellers		2 fixed pitch propellers
Number of rudders		2
Number of side thrusters		3 X Bow, 3 X stern
Fin stabilizers		One pair
Total number of passenger cabins		1 339
Number of crew cabins		650
Max. capacity of persons onboard		4 160

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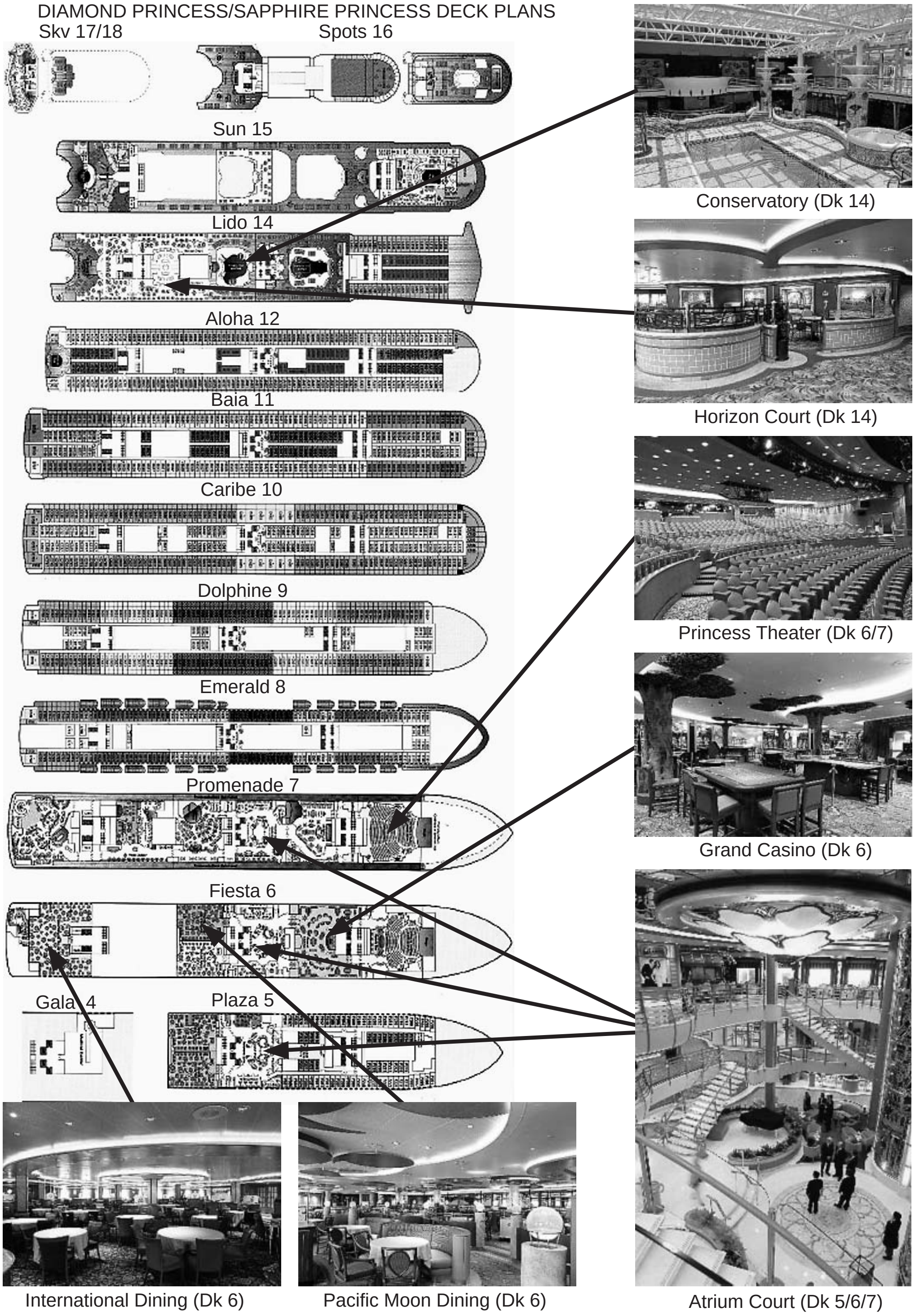

Fig. 2 Arrangement of passenger spaces and major public spaces

2.2 Public spaces for passengers

Meals are one of the main pleasures onboard any cruise ship. Thus, a variety of restaurants are provided under the Princess Cruises' unique concept of Personal Choice Dining in which you may dine “when you like, with whom you like, and wherever you like.” These include one main restaurant; four specialized "theme" restaurants which serve a select range of dishes based on Italian, American steak, Mexican, or Asian menu themes; the Sabatini which specializes in real Italian cuisine; and the Horizon Court, which offers a variety menu 24 hours a day.

An extensive range of public facilities are also provided onboard including various types of lounges that offer passengers many opportunities to relax in an pleasant environment, a large 700-seat theater in which musical and other shows are performed twice a day, a casino where passengers can enjoy an atmosphere similar to that of Las Vegas, an entrance hall with a three-story atrium, one of the largest Internet cafes onboard any ship, a spa with a gym and massage rooms, an indoor pool with sliding roof and large and small outdoor pools, and mini-golf courses.

3. Efforts for environmental protection

In recent years, regulations concerned with environmental protection have become increasingly stringent year by year in cruise sea areas with respect to passenger ships. There have been cases in Alaska, for example, where embargoes and penalties have been imposed on cruise ships for causing environmental pollution of any kind.

As part of measures to implement the environmental policy of Princess Cruises in which the keywords are zero emissions/clean discharge, power generation, propulsion, and waste treatment systems have been adopted onboard the ships described in this report that take advantage of the very latest advances in technology.

3.1 Integrated electric propulsion system

The ship has adopted an integrated electric propulsion system in order to remarkably reduce NOx emissions and to eliminate smoke. The power generating system servicing both hotels and propulsion system consists of four new-generation smokeless middle speed diesel engines and one aero derivative model gas turbine. The electric propulsion system has two propulsion motors and conventional shafting with fixed pitch propellers.

The diesel engines are sitting in the engine room near the bottom of the ship, whereas the gas turbine is located on deck 16 inside the funnel since it is compact in size and light in weight and generates less vibration and noise (**Fig. 3**). This has made it possible to increase the amount of space available for use as passenger spaces.

The generators can be operated with two unequal load sharing modes, i.e. DG priority mode for fuel cost saving and GT priority mode for low smoke emission, as well as an equal load sharing mode in all sailing situation.

3.2 Waste and sewage treatment system

Given the increase in the size of cruise ships in recent years, the number of passengers carried onboard can now easily reach several thousand persons in total. As a result, the treatment of waste and sewage largely produced in the course of life onboard the ship is closed up for environmental protection.

3.2.1 Waste treatment system

Two advanced incinerators (1 600 kW x 2) with flue gas treatment systems are installed onboard to incinerate the waste produced in the ship. The flue gas treatment system is manufactured based on the values specified in German Ordinance BIMSCHV 17, which is one of the most strict discharge standards in the world.

The treatment system consists of a cooling tower, a reactor, and filters, and removes HCl, NOx, SOx, dioxin, heavy metals, and dust from the flue gas of the incinerator and discharges the gas in the form of clean flue gas into the atmosphere.

3.2.2 Sewage treatment system

Sewage produced onboard the ship is treated and purified to a dischargeable condition by a sewage treatment system and discharged outside the ship.

Advanced sewage treatment systems have been installed onboard both these ships in order to remove impurities and reduce BODs, the presence of colon bacillus, the degree of pollution, and solid matter to levels that are about 1/10 those of conventional systems.

A comparison between the IMO and USCG sewage discharge standards is shown in **Table 2**. As can be seen in the table, the discharge standards have been enhanced in the Alaska sea area. Consequently, the treatment systems used onboard both vessels can fully meet the requirements of these stricter standards.

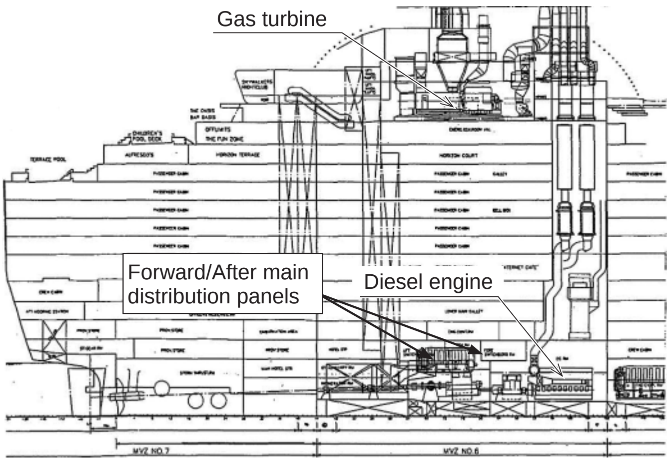

Fig. 3 Arrangement of generators
The diesel engine is located on Deck 1, while the gas turbine has been installed inside the funnel on Deck 16.

Table 2 Sewage Discharge Criteria

Item	USCG 33 CFR 159PT-1-300	IMO MEPC. 2 (VI)	USCG/ Alaska 40 CFR 136
Test period	10 days	10 days	10 days
Suspended solids (mg/l)	150 or less	50 or less (100 at sea)	30 or less
BOD (mg/l)	Not specified	50 or less	30 or less
Number of coprophil coliform groups (pcs/100 ml)	200 or less	250 or less	20 or less
PH value	Not specified	Not specified	6.0-9.0
Chlorine ions (mg/l)	Not specified	Less in practical range	100 or less

4. Measures against smoke emissions

The shapes of the funnel used onboard passenger ships are formed in characteristic shapes depending on the operators and the series of the ships. Although the ships covered in this report are positioned as part of the Grand-series, they have elements that differ from those of last Grand-series vessels. These include the gas turbine being located inside the funnel, a large discotheque is located at the rear of the funnel, and pod-shaped ornaments (GRP-make) in the characteristic metallic silver color of these ships are located on both sides of the funnel. Accordingly, the shape of the funnel was developed to be specific to the design needs of these ships.

The shape of the funnel and discotheque and the decorative structures around them had to be designed so that exhaust gas from the funnel does not come into contact with the open deck, discotheque, decorative tube, or the air intake while making the most use of the appearance design intended by the shipowner. MHI made every effort to optimize the shape of the funnel by wind tunnel tests carried out in cooperation with the MHI Nagasaki Research & Development Center from the basic stages of design.

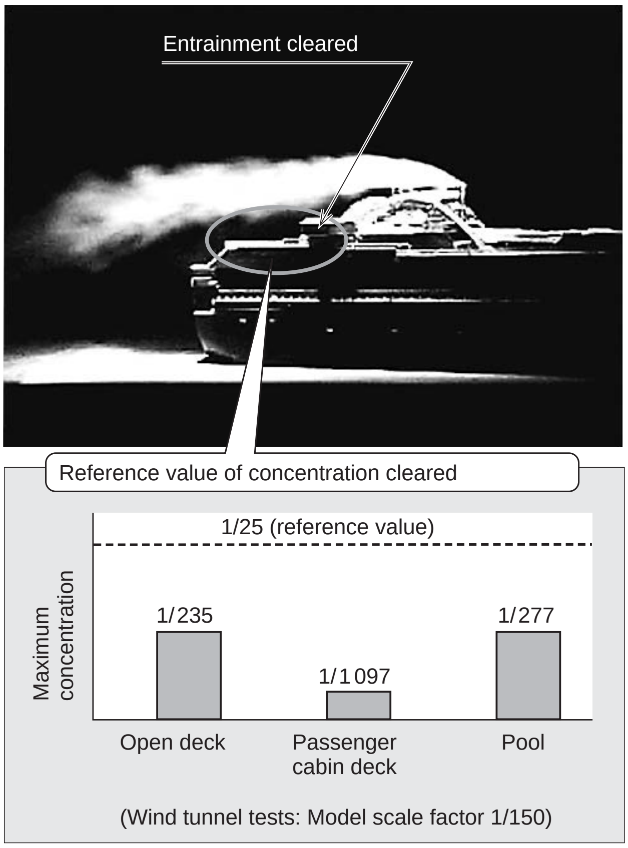

Fig. 4 Results of wind tunnel tests
This figure shows results of wind tunnel tests of the funnel design adopted when the stack is facing against wind in a straight forward direction. The entrainment and trail of the smoke emissions to the open deck are not observed.

Key points in optimizing the shape of the funnel included reducing the size of the gas turbine room, promoting the rise of smoke emissions upwards out of the ship through a collective arrangement of multiple exhaust gas pipes, and the opening ratio (including harmony with the appearance design) of the decorative structures around the funnel.

Figure 4 shows one example of the wind tunnel test results for the shape of the funnel adopted onboard these two vessels. The figure shows that the absence of any entrainment and falling of smoke emissions to the open deck and that exhaust emission concentration requirements are also satisfied.

5. Efforts to reduce vibration and noise

One of the most important factors in determining the commercial value of passenger ships is how quiet and vibration free they are. Hence, reduction of vibration and noise onboard is the most critical technical problem in the successful design of any passenger vessels. In order to reduce vibration and noise as much as possible on these two vessels, MHI has made every effort to develop a low vibration propeller and optimum hull design, and to predict vibration and noise level at the designing stage.

MHI has also carried out exciter tests during the construction stage, conducted investigation and feedback based on measurement of vibration, noise levels and other characteristics during preliminary sea trials at the shipyard. As a result of these efforts, it was possible to confirm that quiet accommodation spaces satisfying the specified requirements could be obtained at the official sea trial.

5.1 Development of low vibration propeller

In developing the propeller for these ships, the propeller design was optimized in order to resolve conflicting requirements such as the need to suppress cavitation while at the same time increase propeller efficiency. Specifically, various types of propeller profiles were prepared, and their performance was evaluated and examined by numerical simulations to narrow down candidate propeller profiles. Then model tests were carried out in order to determine the most suitable propeller to be adopted for these ships.

In addition to the model tests performed at the MHI Nagasaki Research & Development Center, at the request of the shipowner, comparison model tests were also conducted at a large European model basin, in which the propeller developed by MHI and those developed by a third party (European basin) were experimented in the state of the model ship having the propeller at its stern. As a result of the tests, the MHI-designed propeller (inward rotating type) was found to have the best performance in general and hence was adopted for the ships.

5.1.1 Results of full-scale measurement

The results of cavitation observation and measurement of pressure fluctuation made during the preliminary sea trial are shown in **Figs. 5** and **6**. They indicate that, at the maximum outputs of the ships, only chip vortex cavitation and thin sheet cavitation occurred and it was verified that cavitation performance of the actual ships were generally identical to that indicated in the model tests.

In addition, the pressure fluctuation was approximately half of the results in the model tests. Thus, the actual propeller was identified as a low vibration type fully meeting or surpassing the specified requirements.

5.2 Structural design preventing hull vibration

Since these ships adopted an electric propulsion system which is driven by main generators via diesel engines and a gas turbine, the major source of hull vibration was propeller excitation forces. On the other hand, since the upper part of the ship forms the living quarters through its entire length, the hull structures there are formed of combination of low rigidity members with the result that the rigidity of the structures is lower than that of general merchant ships. Therefore detailed investigation on vibration was performed during the designing stage on the basis of prediction of vibration response against propeller excitation at each hull section.

5.2.1 Detailed response calculation of the whole ship

Propeller excitation inputted into the stern part of the hull is transmitted in the longitudinal direction through nodal vibration of hull girder, which in turn generates local vibration of the deck through the pillars and steel walls. In order to quantitatively evaluate this propagation of the vibration, it is usual that the whole ship finite element model is requested.

In general, however, there are limitations in preciseness of the analysis model because of limitations in computer capacity and difficulties in handling the output, when the ship is calculated with an whole-ship model. In the design of these ships, modal propagation analysis technique developed by MHI Nagasaki Research & Development Center was introduced, and detailed vibration characteristics through the entire ship could be studied by coupling the vibration characteristics obtained from each detailed model, which was divided in the longitudinal direction of the ship. A view of the analysis model is shown in **Fig.7**.

The effect of equipment and furniture specific to the passenger ship on the damping effect of vibration was taken into account in the response calculation by predicting them through hammering tests with mock-up cabins.

Against vibration properties of each hull section obtained from these analyses, suitable measures such as reinforcements of structures or additional weight, etc. were taken and incorporated in the structural drawings of the ships according to the degree of avoidance of resonance or the levels of vibration response.

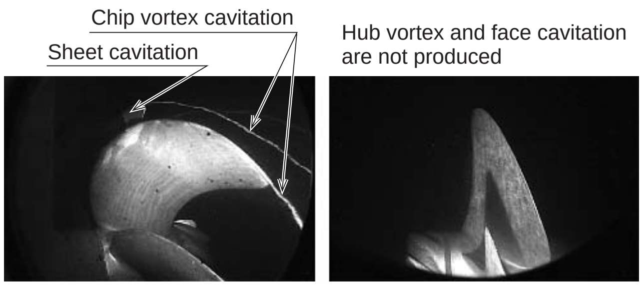

Fig. 5 Results of observation of propeller cavitation
Excellent cavitation perttern could be confirmed similarly to the model tests.

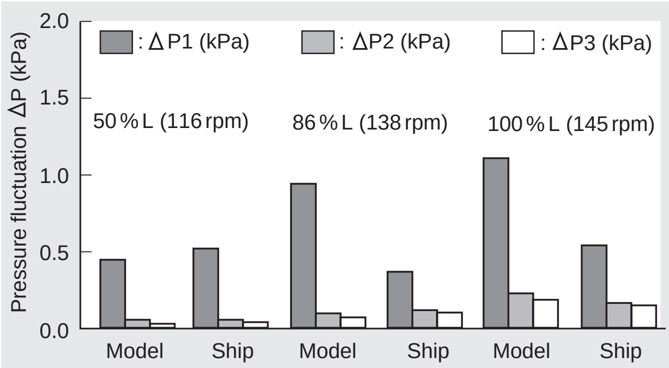

Fig. 6 Results of full-scale measurements of pressure fluctuation
The results of these measurements showed that pressure fluctuation of the ship was about half of those obtained by the model test, and the propeller was confirmed to be low in vibration.

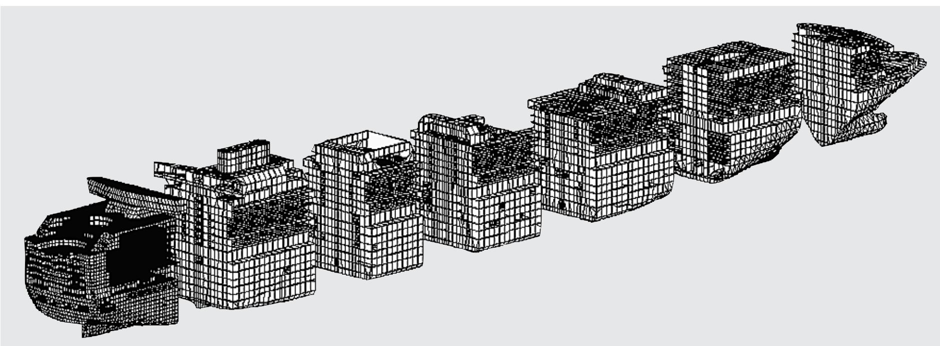

Fig. 7 View of detailed analysis model

5.2.2 Vibration tests on the actual ships and results of hull vibration measurement

The characteristics of vibration propagation from the excitation were investigated during the construction stage by vibration tests of the actual ship using an exciter mounted at the stern part of the ship. Counter measures such as the reinforcement of structures were taken for those portions where excessive vibration response was expected in this test.

As an example of the results of hull vibration measurements during the official sea trial, the distribution of the vibration levels in the longitudinal direction of the ship is shown in **Fig. 8** together with the predicted values by the analysis at the designing stage. It could be confirmed that the required allowable values were satisfied at all measurement points. Moreover, it could also be confirmed that the detailed response analysis adopted this time is sufficiently practical in terms of accuracy.

5.3 Low noise design

Specific noise limits include (1) noise level limits, (2) sound attenuation between accommodation spaces, (3) noise break-in from machinery/systems, and (4) impact noise. MHI has taken the following steps to keep the specified noise limits. As a result, these passenger ships were confirmed to be low noise and comfort cruise vessels.

(1) Control noise level limits

Noise prediction analysis was carried out at the initial design stage for the entire ship. In addition, calculations to predict propeller vibratory force and noise pressure levels at the stern were requested of DNV (the Norwegian classification society), which has an established track record in this field, and the noise prediction analysis were verified.

Plans for noise protection and countermeasure analysis were established based on these prediction calculations, and noise measurements were made at as many as two thousand points during sea trials.

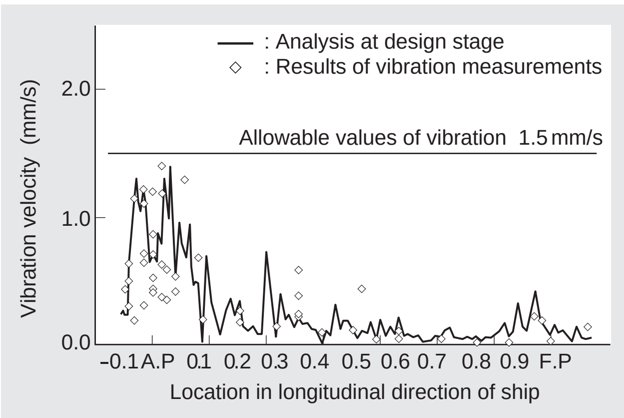

Fig. 8 Distribution of vibration levels in longitudinal direction of ship
The vibration response levels were found to meet the requirements for allowable values at all measurement points, and well matched the values estimated at the design stage.

These measurements and their feedback were repeated to increase the degree of completeness to the extent possible. An example of the noise protection for stern cabins (accommodation space) is shown in **Fig. 9**.

(2) Sound attenuation between cabins (accommodation spaces)

The sound attenuation between the lounge and theater where entertainment is playing and the passenger cabins is regulated. In particular, the places where heavy acoustic insulation, floating floor and visco-elastic floor were applied, were focused our attention to check the noise levels.

(3) Noise break-in from machinery and systems

Differences in the noise levels between equipment in the running or fluctuating condition and in the stopped condition are required to be within a certain noise level (2 to 3 dBA). This is specified in order to prevent passengers from feeling discomfort while sleeping. Detailed anti-vibrating measures for equipment and pipes as well as acoustic insulation measures for surrounding areas were also required, which posed a major challenge for MHI in its efforts to develop suitably effective measures.

(4) Impact noise

This specifies a noise limit in a compartment just below the deck against noise generated by dancing, sports, and the running of working vehicles on the deck. Some noise reducing measures were adopted, such as visco-elastic layer on deck based on test results at a mock-up

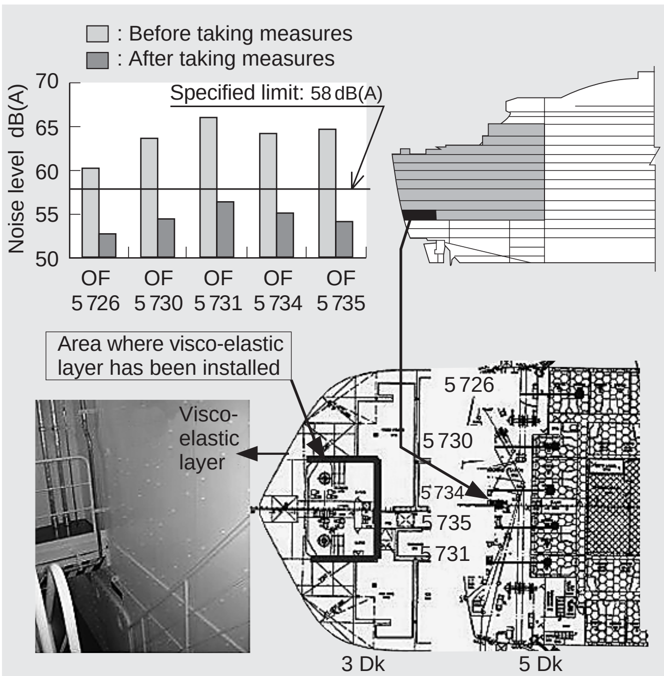

Fig. 9 Example of measures taken against noise at stern compartment
The noise levels in the officer cabins of stern compartment on Deck 5 were reduced to the specified limits or less by installing visco-elastic layers on the walls of the lower decks just above the propeller.

6. Safety and fire protection equipment

A tremendously large volume of information on the various safety and fire protection equipment is required for these ships, which have a total boarding capacity of 4 000 persons or more. These include such things as fire detection system, sprinkler system, fixed type carbon dioxide gas fire fighting equipment, local water fog system, fire doors, water tight doors, and fire dampers in the ventilation duct, and so forth.

In order to properly manage with a tremendously large volume of information at accidental fires and flooding, Princess Cruises has developed a Safety Management System (SMS) to systematically monitor and operate the safety and fire fighting equipment used onboard these ships, and its latest version is also installed onboard these ships.

According to the nature and the location of accident, SMS can present the essential information in an easy-to-observe form with the procedures selected from a large number of predetermined ones to assist the crew in implementing suitable procedures. For example, when a fire is detected, SMS gives the location of the fire with the recommendations to control the relevant ventilation fans, fire dampers and fire doors.

7. Recovery from fire accident during construction

On 1 October 2002, a fire occurred in the passenger cabin of Deck 5 in the first ship which was waiting to go on its first sea trials at the shipyard. As a result of the fire accident, approximately 40% of the hull was burned out, though fortunately, there was no damage or harm to anyone on or near the ship. It was also fortunate that there was no damage to the engine compartment, and the owner and MHI agreed upon on the recovery and continuous construction of the burnt ship.

The names of the two ships were switched. The ship which was being constructed after the first ship that was burned was designated as the "Diamond Princess," and the fired ship was designated as the "Sapphire Princess". The delivery dates of both ships were changed to the end of February 2004 and the end of May 2004, respectively.

This meant that two large passenger ships were for the most part constructed simultaneously at one shipyard, which was the first challenge of its type in the world. The "Diamond Princess" was constructed in this yard in the same manner as before, and the "Sapphire Princess" was moved to the Koyagi repair dock where the damaged portions were completely removed, overhauled, refurbished, and re-constructed.

Fig. 10 Launching ceremony of the Sapphire Princess
Repair work and construction of the ship was successfully completed, after which it was safely launched as the Sapphire Princess.

At the same time, consultations were held between MHI and concerned parties to prevent such an accident from re-occurring, and the fire protection and fire fighting procedures underwent a drastic review and revamping, and the re-vamped procedures were rapidly applied to both ships.

As a result of these efforts, MHI could complete the recovery construction in September 2003 thanks to the cooperation, reliability, and teamwork of all those concerned including the owner and Lloyd's Register of Shipping, and could safely realize the launching of the ship newly named the "Sapphire Princess" (**Fig. 10**).

8. Conclusion

Although the construction of passenger ships has mainly been a specialized task performed by four leading European shipyards, MHI has demonstrated through the construction of these ship that it can also claim a place as one of the world's leading builder of passenger ships and that the Japanese shipbuilding industry is superb.

On the other hand, the cruise market has already recovered from a recession that hit the market since the terrorist attacks in the U.S. on 11 September 2001. The remarkable growth seen in recent years in the cruise market, which mainly consists of the US market and European markets, is expected to be maintained for some time to come and is expected to result in a sustainable demand for about eight large passenger ships per year in the foreseeable future.

Drawing upon the experiences gained in the construction of these two ships, MHI will make every effort to further improve and construct passenger ships continuously as a major Japanese shipyard for passenger ships.

Lastly, MHI would like to express its sincere appreciation to Princess Cruises and to Lloyd's Register of Shipping who greatly guided and extended cooperation to us during construction of both ships, as well as to everyone involved with the construction of these two ships.


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