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Review

Full-scale Experiments of JCG Patrol Vessel SOYA from 1991 to 2013 in the Southern Sea of Okhotsk

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Abstract

The winter navigation in the southern Sea of Okhotsk needs ice-strengthened vessels due to sea ice. In this region, the Japan Coast Guard has operated patrol vessels, such as P/V SOYA, capable of ice navigation and provided valuable opportunities for ice observation and ship ice trial. National Maritime Research Institute took part in such cruises for twenty-three years and conducted full-scale onboard experiments regarding ice conditions and ship performances in ice. This paper overviews the experiments with the measurement results of ice concentration, ice thickness, ice load on the hull, and shaft power required in ice. The long-term data accumulation in response to various ice conditions would contribute to the design and operation of forthcoming Japan Coast Guard patrol vessels.

Key words: ship characteristics in ice, icebreaker design, onboard measurement

1. Introduction

The Sea of Okhotsk is the southern limit, in the Northern Hemisphere, of drift ice usually coming ashore along the coast of Hokkaido between late January and early March. The Japan Coast Guard (JCG) deploys the patrol vessels (P/Vs) SOYA and TESHIO, which can operate in ice-covered waters with ice-breaking ability to deal with maritime accidents in drift ice. National Maritime Research Institute of Japan (NMRI) conducted full-scale experiments in ice onboard P/V SOYA (Fig. 1) and supplementally P/V TESHIO from 1991 to 2013 in the coastal area of Hokkaido, and the most of these experiments were conducted under a joint research agreement with the Ship Division, Equipment and Technology Department of the JCG. The above research series is referred to as the Joint Ship Research or abbreviated to the JSR. In this paper, we discuss the experiments onboard P/V SOYA.

Fig.1 P/V SOYA operating in ice

The purpose of the JSR was to study the sea ice conditions in the southern Sea of Okhotsk, and to clarify ship performance in ice-covered waters, and hull loading caused by contact with ice (hull ice load) through observations based on the actual vessel and to collect practical information to the development of forthcoming P/Vs of JCG operated in ice.

One of the worthiness of the series of experiments is the long-term data accumulation in response to various ice conditions repeatedly obtained by the same vessel. Sea ice in the southern Sea of Okhotsk is first-year ice showing various forms in respective years. Therefore, the data contains ice contact events experienced in various ice conditions and reveals the operation profile of the patrol vessels in ice.

The results of these experiments have been published in various forms and literature. However, there have been few reports that summarize overall experiments. This paper summarizes the results of the JSR obtained onboard P/V SOYA. The comprehensive measurements of ship characteristics in the southern Sea of Okhotsk for decades have been rarely reported yet due to the lack of icebreaking operation experiences by Japanese vessels. These measurements provide a unique dataset for icebreaker design and winter navigation in the Sea of Okhotsk.

2. Outline of the Full-scale Experiments

Figure 2 shows the history of the full-scale experiments conducted by NMRI onboard JCG P/Vs. In

1991, NMRI started full-scale experiments in the ice-covered area along northeastern Hokkaido onboard patrol vessels in collaboration with JCG. P/V SOYA has been the most eligible for the purpose, whereas P/V TESHIO was temporarily engaged several times since its launching in 1995 (Koyama *et al*., 2000.) Since 1996, P/V SOYA and the 1st Regional Coast Guard Headquarters have provided annual scientific cruises in the middle of February along the route planned shown in Figure 3 mainly for sea ice observation mission in cooperation with Institute for Low Temperature Science (ILTS), Hokkaido University and other academic parties. NMRI had taken these opportunities to carry out a variety of measurements for engineering purposes until 2013.

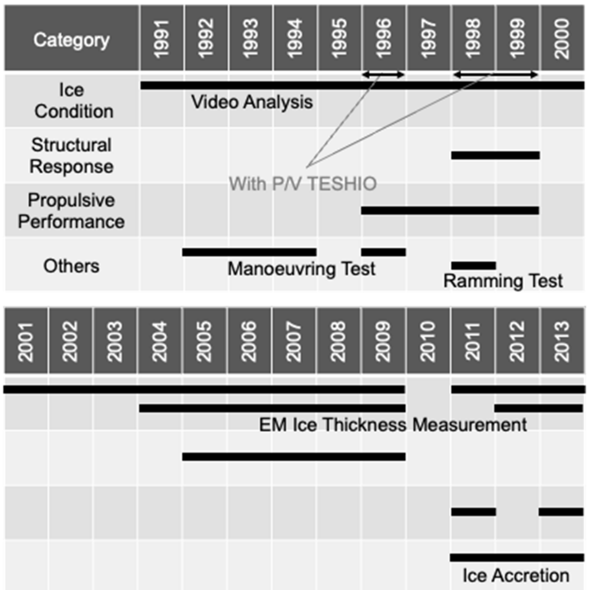


Fig. 2 History of Full-Scale Experiments by NMRI onboard JCG P/Vs

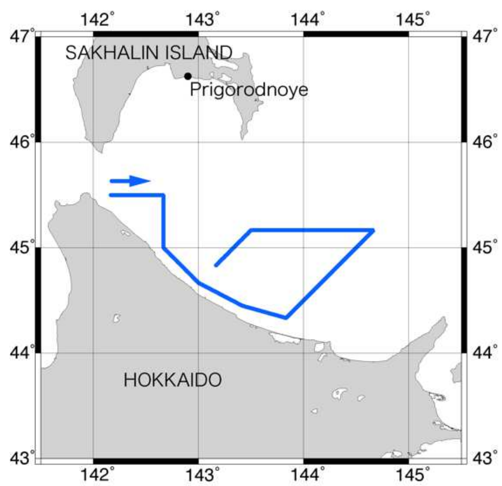


Fig.3 Typical route in the scientific cruises of P/V SOYA in the southern Sea of Okhotsk

P/V SOYA was constructed as the first patrol vessel capable of carrying a helicopter in JCG and entered service in 1978. Table 1 shows the principal dimensions. The hull is ice-strengthened to the level approximately equivalent to IA Super in the Finnish-Swedish Ice Class Rules (FSICR). P/V SOYA has a twin-shaft diesel propulsion system equipped with controllable pitch propellers (CPP), providing power for the ice-breaking ability for level ice of 1.0m thick. In addition, anti-rolling tank and retractable fin stabilizers are equipped to suppress adverse rolling in helicopter operation.

Table 1 Principal Dimensions of P/V SOYA

Item	Unit	Value
Length Overall	(m)	98.6
Length Waterline	(m)	90.0
Breadth Molded	(m)	15.6
Depth Molded	(m)	8.0
Draft	(m)	5.2

The significant parameters obtained onboard icebreakers for engineering purposes are:

a. ice concentration and thickness as environment condition,
b. hull structural response for hull ice load, and
c. shaft thrust and torque for propulsion performance in ice.

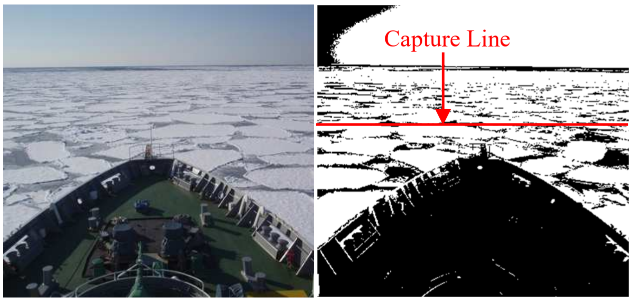
The ice concentration and thickness measurements were carried out in collaboration with the onboard scientific observation conducted by ILTS, and the results have been combined in the annual reports (ILTS, 1996-2022.) We also measured the hull structural response, the thrust, and the torque together with the above scientific observation. The results of these measurements are respectively explained later.

3. Ice Conditions in the Sea of Okhotsk off the Hokkaido Coast

From an engineering point of view, ice properties such as ice concentration, thickness, floe size, and mechanical strength are essential parameters for the design and operation of ice-going vessels. In this region, ILTS has continued the long-term visual observation of sea ice features based on ASPeCt protocol initially proposed for Antarctic ice, which reveals that the dominant thickness categories are thin first-year ice (from 0.3 to 0.7m) and nilas (under 0.1m) during recent 20 years, for example. It is also reported that the average thickness is 0.28m for level ice and 0.65m for ridged ice, which indicates that the ridging process is vital for the growth of ice thickness in this area.

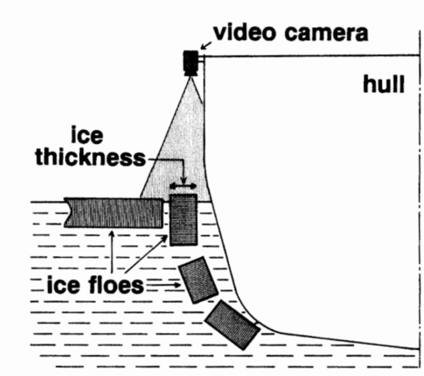
NMRI adopted the ship-borne video analysis methods for sea ice concentration and thickness. Figure 4 shows the analysis method of ice concentration. Ice concentration is automatically calculated by pixels on the fixed horizontal line in each binarized video frame of the front view.

Figure 5 shows how to measure ice thickness from video images. Ice thickness is directly measured from downward-looking views in which a broken ice piece stands the side-up position (Shimoda *et al.*, 1997). Figure 6 shows the histogram of total thickness from 1991 to 1998 (Uto *et al.*, 1999) by the video analysis method. Here total thickness denotes the sum of ice thickness and snow depth. Although this method is accurate for undeformed ice, it is difficult to obtain data of very thin or thick deformed ice.



(a) (b)

Fig. 4 Example of captured video frame of front view (a) and binarized image (b) used for calculation of ice concentration



(a)

(b)

Fig. 5 Schematic diagram (a) and photo (b) of ice thickness observation by hull-side video camera (Shimoda *et al.*, 1997)

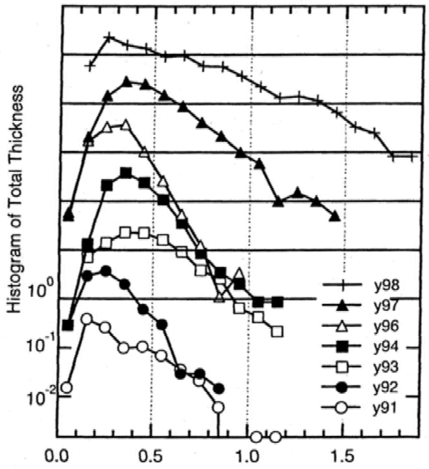


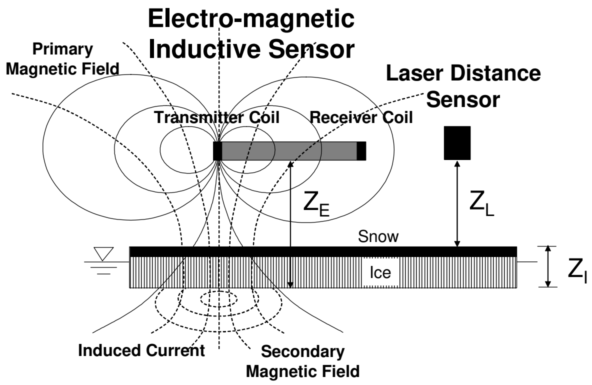
Fig. 6 Histogram of Total Thickness by Video Camera from 1991 to 1998 (Uto *et al.*, 1999)

Thick deformed ice, such as ridged ice, is one of the main concerns for ships in ice. In February 2004, NMRI introduced the ship-borne electromagnetic induction (EM) ice thickness observation technique. Figure 7 shows the principle of EM ice thickness measurement and its onboard installation. The EM sensor and the laser altimeter measure the distance to the ice bottom; Z_E and the distance to the snow surface; Z_L, respectively. Thus, the total thickness beneath the sensors; Z_I is calculated as:

$$Z_I = Z_E - Z_L$$

It enables us to continuously observe the thickness of ice, including ridged ice, with reasonable accuracy. Figure 8 shows the total thickness variation measured by the EM method during 2005-2009. Uto *et al.* (2006) proposed a method for improving the measurement accuracy of the thickness of ridged ice. The conversion algorithm from EM output to Z_E is developed by incorporating the internal structure model of ice derived from drill-hole measurements in the southern Okhotsk Sea. However, further research is required for the accurate measurement of the thickness of ridged ice.

By combining the above methods, we can continuously observe the ice condition along the ship track. Figure 9 shows an example plot between ice concentration by the video method and ice thickness by the EM method. Since the data sampling intervals are different between the two ways, all sampled data are averaged for each 2,000m advance of the ship. This plot helps overview the ice severity through voyages. In 2005 and 2006, the ice condition was relatively severe with thick ice, while it degraded after 2007. The ice concentration scatters similarly both in 2005 and 2007, however, the ship should experience more difficult navigation in 2005 due to the ice thickness of over 1.0m.



(a)

(b)

Fig. 7 Principle of EM sea ice thickness measurement technique (a) and EM equipment extended from the hull-side of P/V SOYA (b) (Uto *et al.*, 2006)

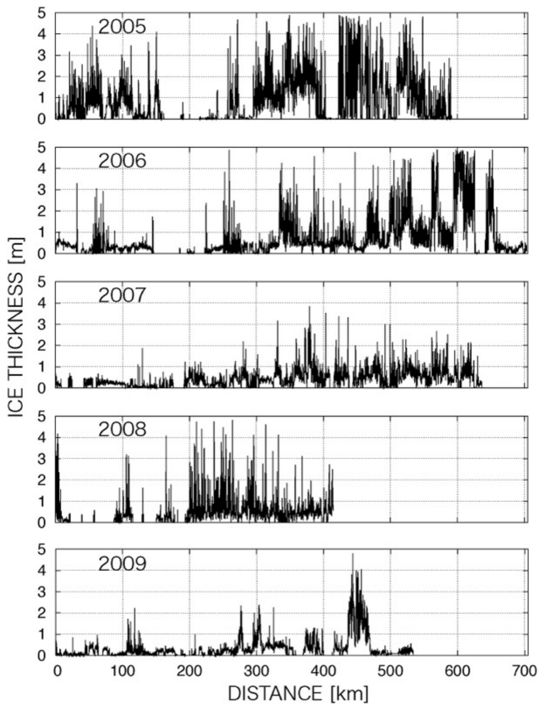


Fig. 8 Examples of total thickness measured by EM during 2005-2009 (Matsuzawa *et al.*, 2010a)

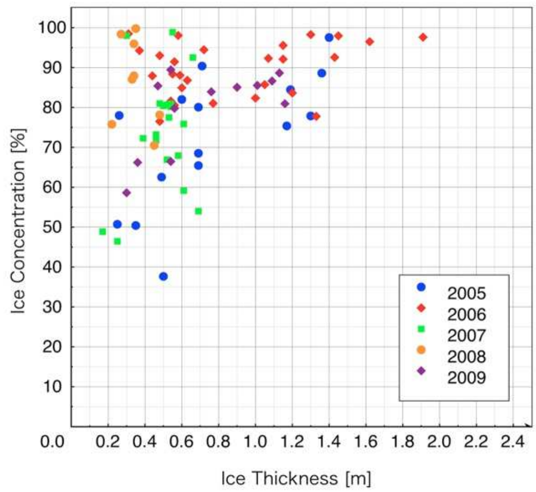


Fig. 9 Correlation plot between ice concentration and ice thickness during 2005-2009 (Matsuzawa *et al.*, 2010b)

4. Structural Response

Measuring hull ice loads is essential for evaluating the structural safety of ships in ice, and the results provide the base data for designing hull structures and structural requirements in ice-class rules. However, unlike the Baltic Sea, such data were rarely obtained in the Sea of Okhotsk.

Figure10 shows the installation of ice load measurements. Shear strain gauges were installed on frames of four sections at the bow and the bow shoulder. Two sets of shear strain gages were installed across the position where the ice load is expected to act. The strain gages were calibrated at least twice a day when SOYA stood for hydrographic survey or at night. The line load of ice acting on the hull was estimated using a couple of measured shear strains in respective frames. Ideally, the conversion factor from strain to load is obtained by physical calibration, such as pushing or pulling the hull. However, there was no such opportunity in the JSR. Thus, an FE analysis was carried out to obtain the conversion factor for each section.

During the ice load measurement, the video camera and the EM sensor synchronously recorded the ice concentration and the ice thickness, respectively. This measurement was conducted from 2005 to 2009. Figure 11 shows an example of the ice load at the bow section (Sec.2 in Fig.10(a)). The ice load estimated from the 2005 and 2006 measurements is plotted against the effective ice thickness. Here effective ice thickness is defined as the averaged ice thickness divided by the averaged ice concentration. The dotted lines in Fig. 11 indicate the design ice loads specified in the Finnish-Swedish Ice Class Rules. The observed results are well below the design ice load both at the bow and in the mid-part of the hull.

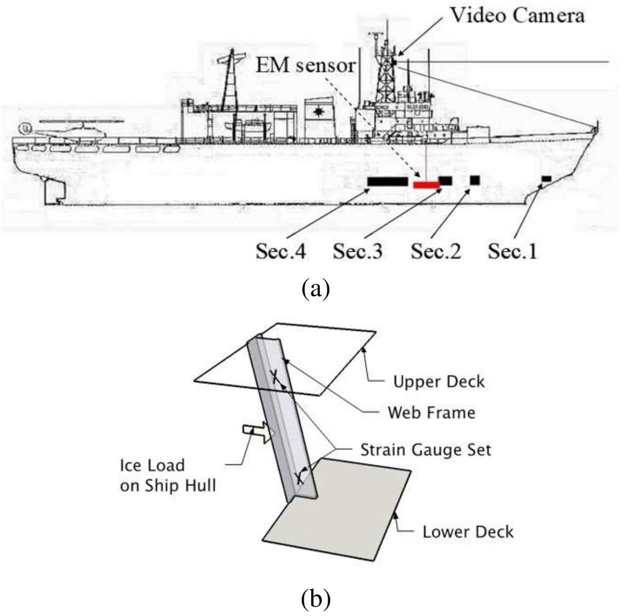


Fig. 10 Layout of ice load measurement instruments on P/V SOYA (a) and schematic of strain gauge installation on a frame (b) (Matsuzawa *et al.*, 2009)

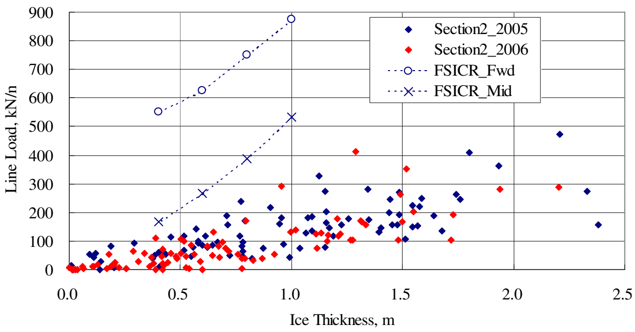


Fig. 11 Correlation between ice loads and effective ice thickness (Takimoto *et al.*, 2007)

5. Propulsive Performance

Various models and numerical simulations have been developed to evaluate ship resistance and propulsive performance in ice. To verify the validity of these models and simulations, collecting propulsive performance data in ice conditions is necessary. Thrust data is beneficial because it is comparable directly with estimated resistance. However, it is difficult to keep its measurement accuracy.

In the JSR, we installed strain gauges on the portside shaft and measured compressive and torsional strain (Fig. 12) to obtain thrust and torque. These measurements were conducted on cruises in 1997, 2011, and 2013. The shaft speed was measured by a photoelectric sensor. The CPP blade angle and ship speed were recorded by reading its indicator and a GPS, respectively.

Suzuki and Nakato (1990) reported the pros and cons of two strain-gauge configurations, i.e., "Conventional" and "Hylarides," used for the thrust measurement. In the JSR measurements, the "Conventional" method was adopted because it effectively eliminates thermal strains to compressive strain with a better S/N ratio. However, when using the configuration, a careful and precise setting of strain gauges was required because the angular misalignment of strain gauges results in the cross-coupling between torsional and compressive strains. The clockwise and counterclockwise shaft turning at a low rotation rate were conducted before the speed trial to obtain the correction factor for the cross-coupling effect.

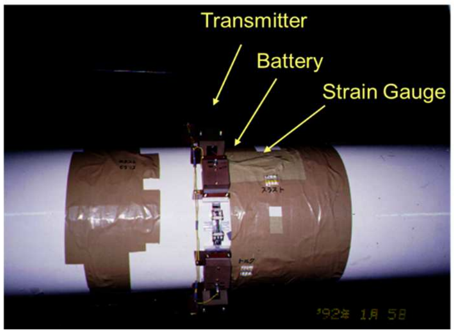


Fig. 12 Configuration of shaft output measurement

Uto *et al.* (1999) conducted an uncertainty analysis of the thrust measurement in February 1997. Figure 13 shows the results of the thrust measurement with the 95% confidence interval as an error bar. Thrust at a ship speed of approximately 4 knots in a 94 cm-thick ice was 386 ± 52 kN. The 95% confidence interval is within ± 13.5% of the average thrust. Removing the cross-coupling effect and minimizing the zero-drift resulted in relatively good accuracy for the thrust measurement.

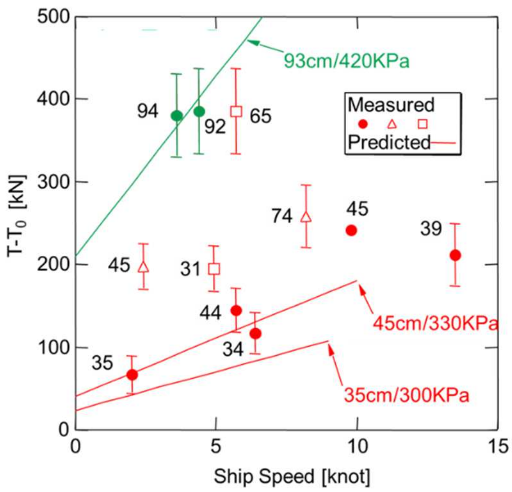


Fig. 13 Thrust vs. ship speed (Uto *et al.*, 1999). T denotes the raw thrust. T0 is the thrust measured at zero angles of CPP blades before speed trials. Both thrusts were measured on the port-side shaft.

Although many mathematical models and simulations are proposed, ice tank experiments are still acceptable as the most reliable method for predicting ship propulsive performance in ice. Thus, the model-ship correlation of propulsive performance in ice is one of the most critical tasks in the hull shape design of ice-going vessels. We conducted the resistance tests of a scaled model of P/V SOYA in level ice at the ice model basin of NMRI. The resistance model of P/V SOYA in level ice was derived from the regression analysis of experimental data. Thrust is calculated by dividing resistance with the thrust deduction factor.

Figure 13 plots the predicted thrust on the port-side shaft versus ship speed from ice tank experiments for a particular ice thickness and flexural strength. Here, the predicted thrust is halved, assuming both shafts share an equal thrust. It shows fair agreement between full-scale measurement and prediction by the model experiment.

Uto *et al.* (2015) proposed the hybrid model of resistance prediction for ships navigating in floe ice, such as small ice floes, large ice floes, and an ice-clogged channel. The accuracy of the model was validated through comparisons with the model-scale experiments conducted at the ice model basin of NMRI and the full-scale thrust measurements (Fig. 14). It is found that the proposed model can predict the resistance in floe ice of various sizes and concentrations with reasonable accuracy.

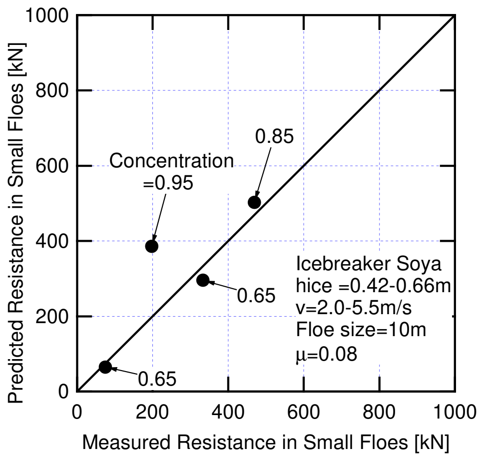


Fig. 14 Comparison of Resistance in Small Floes between Measured and Predicted (Uto *et al.*, 2015)

6. Conclusion

The results of the full-scale experiments conducted onboard the Japan Coast Guard patrol vessel SOYA in the Sea of Okhotsk off the coast of Hokkaido are summarized. The long-term data accumulation over more than twenty years would contribute to the design and operation of forthcoming patrol vessels of the Japan Coast Guard. Although it has been challenging to conduct such large-scale and long-term experiments in Japan in recent years, we conclude this article by pointing out the importance of taking every opportunity to obtain data from such experiments to advance ice engineering research.

Acknowledgment

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