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（東京大学大学院　新領域創成科学研究科　海洋技術環境学専攻）

Research on Sudden Change of Wind Condition and its Effect on Safe Offshore Operation in the Sea near Japan

学籍番号 47136803　　盧　永建
指導教員　　尾崎　雅彦　教授

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1. Introduction

1.1 Background

The sudden change of wind condition called “squall” has become paid attentions recently in West Africa. Squall is a meteorological phenomenon which associates the sudden change of wind speed from low/mild to high and wind direction up to 180 degrees within a few minutes. It is one of important considerations in designing Floating Production Storage and Offloading system (FPSO) in West Africa. Squall events in the Gulf of Mexico are also highlighted very recently with maximum wind speed of 40 m/s [1].

Most researches focus on their effects on the mooring systems of FPSOs and the statistical characteristics of squall. But a reliable squall model is still not clear, especially for the extreme analysis. Moreover, the existing literatures show little attention on the meteorological environment of squalls’ formation. Besides, there are few studies of the effects of squalls on offshore operations, rather than mooring systems.

1.2 Research objectives

As the increase of offshore operations in the sea near Japan, such as carbon dioxide capture and storage, wind farm construction, production test of methane-hydrate, deep ocean mining and ultra-deep ocean drilling, this kind of sudden change of wind condition should receive additional consideration. Until now hardly any research was carried out on squalls on the sea near Japan. Therefore, the study conducted in this thesis focuses on the understanding of the meteorological environment and the mechanisms of sudden change of wind condition, investigating the existence of squalls on the sea near Japan, finding the suitable squall models for ocean engineering, and evaluating the effects on offshore operations.

2. Sudden change of wind condition on the sea near Japan

2.1 Squall and Squall line

According to the World Meteorological Organization (WMO), the criteria for reporting “squall” is a sudden increase of wind speed of at least 8 meters per second, the speed rising to 11 meters per second or more and lasting for at least one minute. While “gust” is a sudden sharp increase in or rapid fluctuations of wind speed. The duration of a gust is usually less than 20 s. In this study, the squall caused by a weather system called “squall line” is mainly studied, which is difficult to forecast. A general definition of squall line is a narrow band of thunderstorm, and always happens in front of cold front [2]. Squalls caused by some other sudden developed weather systems are also emphasized.

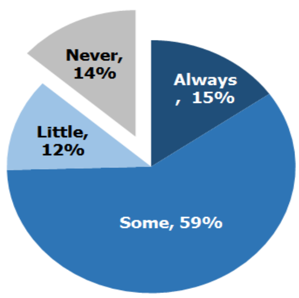


Fig.1 The frequency of experiencing the danger of suffering sudden change of wind condition.

2.2 Squall investigation by questionnaire survey

A questionnaire survey was carried out and distributed in 6 companies and agency. A total of fifty-nine usable responses were received and all of the respondents are the staffs with working experiences on offshore operations. According to the survey results, only 14% respondents have never felt the dangers brought by sudden change of wind condition. Seventy-four of percent respondents have experienced the danger of sudden change of wind condition in offshore operations (Fig.1). Based on the results in this survey, sudden change of wind condition mainly happens in the situations as shown in Tables 1. In summary, sudden change of wind condition does exist on the sea near Japan. However, the detailed changing process of wind condition and the weather environment for the sudden change of wind condition needs further studies.

Table 1 Sudden change of wind condition based on questionnaire survey.

◉ Wind changes inconsistently with forecasting	The strength
	The arriving time
◉ Change happens under no forecasting	
◉ Change caused by topography (ex.cliffs)	
◉ Speed increases suddenly and rapidly	With changing wind direction
	Without changing wind direction

2.3 Squall preliminary investigations by floating buoy data

Data from the NOAA Kuroshio Extension Observatory

(KEO) buoy and JAMSTEC Kuroshio Extension Observatory are used to screen squalls on the sea near Japan. All the data have an interval in measurement of 10 minutes. The results show that squall events very likely exist on the sea near Japan. However, most of them just reach the requirements to be a squall. Besides, mean wind speed in every 10 minutes cannot show the most severe situation in the change process. Wind data collected in a shorter duration is necessary for further study on the squalls' features on the sea near Japan.

2.4 Squall investigation by remote islands data

For the matter of squall data, a joint industry project (JIP) The West Africa Gust (WAG) [3] was formed to measure squall wind data in West Africa. Until now, no observatory is established to observe the squalls on the sea near Japan. Because Japan has lots of remote islands, this advantage is taken to further investigate the occurrence of squall in this study, where wind data are recorded by meteorological observatories in every 1 minute. In order to screen squall in large quantities of data, a screening standard and program is made for this problem. *Minamidaito-jima* and *Hachijo-jima* are selected to study. Fifteen squalls are found in *Minamidaito-jima* (2003 ~ 2013) and 3 of them were caused by typhoon on the basis of weather maps. In *Hachijo-jima* (2004 ~ 2013), thirty-one squalls were found and 8 of them might be caused by typhoon on the basis of the weather maps.

- **Case A: Short duration squall caused by squall line**

This squall happened on 25 November 2013, in which wind speed suddenly changed at around 14:00. The change of wind speed on that day is shown in Fig.2 (Upper) and its detailed process in Fig.2 (Lower). Wind speed suddenly increased at 13:40, from about 10 m/s to 27.5 m/s in 12 minutes, and lulled in the following 10 minutes. At the same time, the wind direction changed from south to near north, almost 180 degrees. By extracting the cloud data from GPV weather data, the sum of high, medium and low cloud cover around *Minamidaito-jima* is processed and obtained. At 9 o'clock in the morning, a broken line shape of cumulonimbus clouds passed the Island of Okinawa (Fig.3A). It was weak at first but became stronger and moved towards *Minamidaito-jima*. At 3 o'clock in the afternoon, the narrow band of thunderstorms was formed and the full development part passed through *Minamidaito-jima* (Fig.3B). It is noteworthy that the narrow band developed much stronger and located in front of cold front subsequently (Fig.3D).

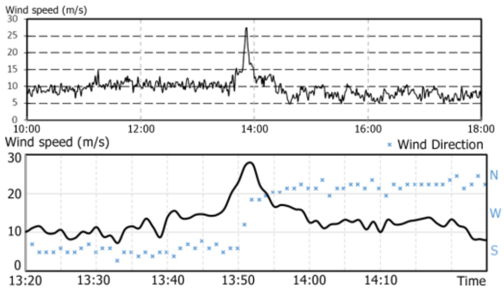


Fig.2 Wind condition of Squall Case A.

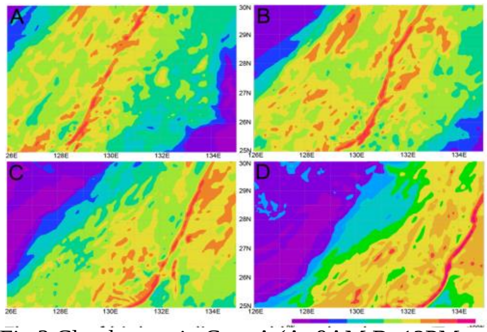


Fig.3 Cloud cover in Case A (A: 9AM B: 12PM C: 3PM D: 6PM).

- **Case B: Continuous squall**

Another squall case that deserves mention is the squall happened on 10 October 2011. Fig.4 shows the change of wind speed on that day and the sudden change began at around 15:00. From Fig.4, wind speed increased from 3 m/s at around 15:43 and reached 18.6 m/s in 10 minutes. Unlike the case A, wind speed continues in a high level for a long time. The wind direction also had a great change, but it happened much earlier than the time that wind speed began to change. According to the weather map, no cold front or cyclone happened near Okinawa prefecture at 9:00 on that day. The sum of high, medium and low cloud cover on that day are shown in Fig.5. Only small clouds existed at 9 o'clock near *Minamidaito-jima* (Fig. 5A). Through the wind vector, the wind was very steady at that time. However, the cumulonimbus developed suddenly and moved close to the *Minamidaito-jima* in next 6 hours (Fig. 5B & Fig. 5C). The wind also became stronger and blew to the island. Thus, the squall is mainly caused by this developed cumulonimbus. After that, the cumulonimbus became weak and still stayed near *Minamidaito-jima* (Fig. 5D). Steady but strong wind continued blowing to the island. Therefore, this squall might be triggered by the other meteorological phenomena that formed suddenly rather than a pre-frontal squall line or the one caused by Intertropical Convergence Zone (ITCZ) in West Africa. Further information is needed to study this case.

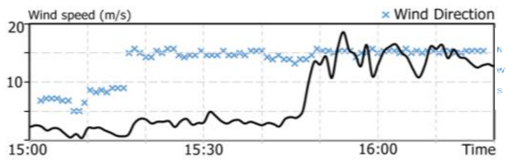


Fig.4 Wind condition of Squall Case B.

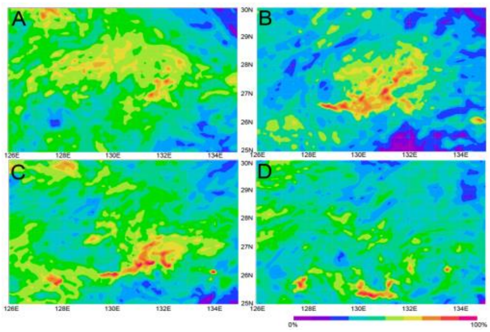
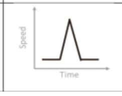
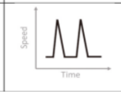
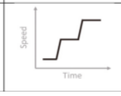
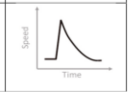


Fig. 5 Cloud cover in Case B (A:9 AM B: 12PM C: 3PM D: 6PM).

3. Squall Simulation Models for Offshore Operation

In order to verify the safety and reliability of offshore operations when suffering from squalls, it is very important to determine squall models for simulations and experiments. Five types of squall models have been tentatively abstracted and classified by the changes of wind speed based on the cases which were found in *Minamidaito-jima* and *Hachijo-jima*. Among the five models, Double-aiguille type, Ladder type and Slow-return type are to some extent derived from Single-aiguille type as well as Continuous type. Therefore, Single-aiguille type (Squall A) and continuous type (Squall B) are selected to be representative squall models for offshore operations simulation in this study.

Table 2 The summary of the classified squall models.

Model Types	Single Aiguille	Continuous	Double Aiguille	Ladder	Slow Return
Features					

4. Questionnaire Survey for the Effects of Squall on Offshore Operations

Same questionnaire investigation in Section 2.2 is also carried out to understand what kinds or which parts of offshore operations may be affected by a sudden change of wind condition. Besides, forecast methods of sudden change of wind condition on the sea are also heard in the questionnaire. Fifty-nine usable responses from 6 affiliations are collected and half of the respondents have worked in offshore operations for more than 10 years.

On the basis of survey responses, when suffering from a sudden change of wind condition, the operation ship and the lifting and recovery systems on board will be affected. Further effects may happen and cause the damages of ship or equipment on board, moreover, the expensive laboratory equipments. On the other hand, different kinds of forecast methods or data are applied to deal with the sudden change of wind condition, but the precision is still a problem. The strength as well as the arriving time of changes of wind condition sometime are inconsistent with the forecast. Besides, wind condition may change suddenly under no forecasting. Although this kind of phenomenon is less strong than typhoon and sometime lasts for a short time, it can bring adverse effects on offshore operation rather than ship capsizing. In particular, an operation ship with DP system may fail to keep her positions when confronting with the sudden change of wind condition.

5. Effects of Squall on Operation Ships with DPS

Simulations have done to know the performance of DP system by using squall models obtained in this study. The principal dimensions of ship simulation model are shown in Table 3. A one-dimensional simulation program is made by Simulink and verified through comparing with the results obtained in a two-dimensional program called DP-MAP, developed by Mitsubishi Heavy Industries. The allowable movement region of the ship is within a 20 m radius in the condition of steady wind of 15 m/s. The naming rule of squall model, take A-25-300 for example, means squall type A with peak wind 25 m/s, rising from 5 m/s in 300 seconds (Fig.6). Fig.7 shows the ship hardly can resist a steady wind speed from B-20-300, mainly staying near the edge of the zone. Relative to this continuous phenomenon, when suffering from a short-term phenomenon squall A, the DP system can handle A-20-300. However, the positioning fails if the peak of wind speed in squall model A reaches to 25 m/s. Therefore, squall A happens in an extremely short time but it can also result in the failure of positioning if the peak of wind speed is more than a certain degree of the designed value.

One-dimensional simulations are carried out with the effect of lateral wind only (Fig.8). Similar results as in DP-MAP are obtained. The ship moves away the allowable zone in A-20-300 case (Fig.9-① left) and cannot move back to the desired position in B-20-300 case (Fig.9-② left). By adding wind feedforward control (WFF, a controller that measure the wind condition and output the necessary thrust to counteract the wind forces on the ship in advance), short measurement time of wind can improve the capability of resisting squall (Fig.9-①middle, ③middle & right) and it is no need extra thrust (Fig.9-④left & middle). By adding integral control, the capacity of resisting squall increases but it brings destabilization

Table 3 The principal dimensions.

Length	89.6 m
Breadth	14.6 m
Depth	6.9 m
Draft	5.6 m
Displacement	6000 ton
Transverse metacentric height	7.5 m
longitudinal metacentric height	120.0 m
Azimuth propeller	3000 kW
Side thruster	1150 $kW \times 2$
Wind area (Lateral)	924.0 m^2
Wind force coefficient (Lateral)	0.8775

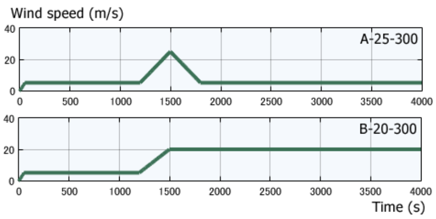


Fig.6 The squall models in simulation.

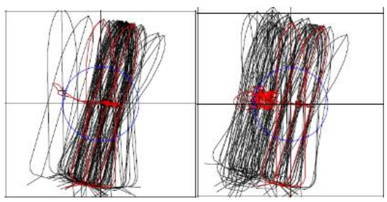


Fig.7 Trajectories of the ship in squall A-25-300 (left) & B-20-300 (right) by DP-MAP.

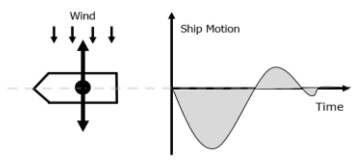


Fig.8 The image of DP system simulation.

(Fig.9-①②right) to the motion and the output of thrust (Fig.9-④right). This can result in the increase of energy consumption and the abrasion of propulsion system. Adjusting the integration time (the time interval of outputting an integration value) can change the destabilization from integral control. As shown in Fig.9-⑤, it turns better if the sampling time is 60 s, but it becomes worse with a sampling time of 210 s. The maximum movement increases with elongating integration time in both squall A and squall B. Significantly, it increases rapidly after the integration time is about 100 s (Fig.10), which seems have certain relations with the ship's natural frequency (210 s). It should be noted that, suitable measurement time of WFF control may steady the ship in heavy destabilization (Fig.9-⑥). In addition, for squall A in a short time, the joint effect of WFF and PID control will increase the opposite displacement of the ship and the probability of moving out the safe operation zone for some offshore operations (Fig.9-⑦).

By using Davenport spectrum, squall models are turned into fluctuating wind form. The gust with higher speed than the mean wind speed appears. However, the simulation results show little different from the original models. On other hand, by comparing with the motion caused by fluctuating wind, higher wind speed caused by gust almost does not affect the performance of DP system. While the squall, a sudden change of wind condition in a relatively long time, can bring adverse effects on DP systems with motion outside its control, resulting in problems in offshore operations.

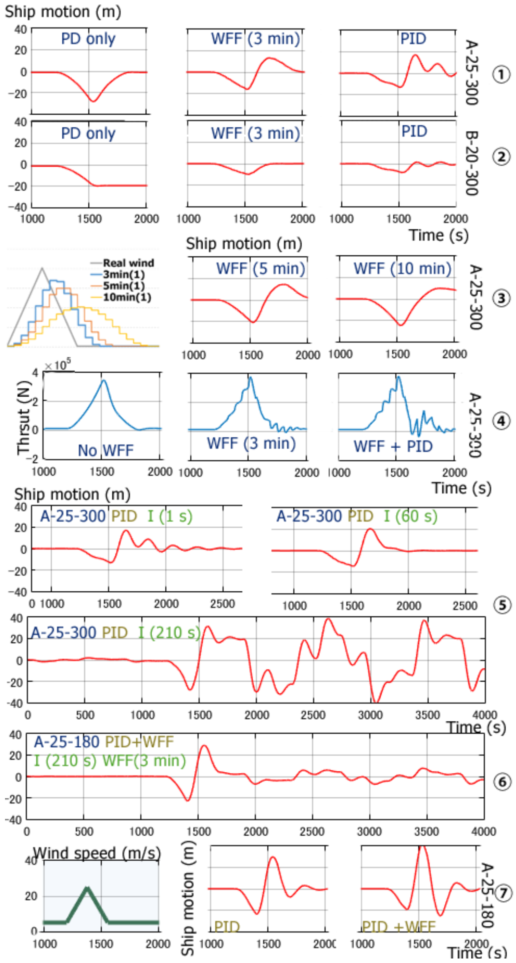


Fig.9 Simulation results in 1D program.

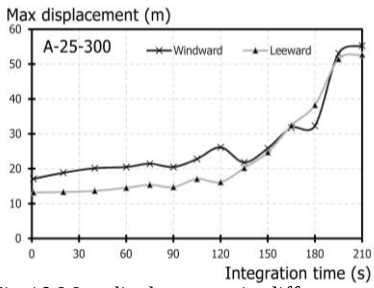


Fig.10 Max displacement in different integration time.

6 Summary and Conclusions

- **Squalls on the sea near Japan**

Screening in the wind data of floating buoys and observation stations at remote islands proves that squall does exist on the sea near Japan. The same results are also proved by experienced offshore workers through the questionnaires. In particular, squall caused by squall line is also found on the basis of weather map and GPV weather data. Case studies explain its danger with unpredictability and its changing process. Other kinds of squalls with different features are also obtained, some of which show different features compared with the typical one in West Africa. Based on analysis results, five kinds of squall models are tentatively proposed. Two are used for simulations on offshore operations as representatives.

- **Effects on offshore operations**

Questionnaire survey shows that the effects of sudden change of wind condition act mainly on the operations on board and the motion of the ship. For the operations on board, the problems mainly come from the lifting and recovery systems of equipments. Besides, the motion of ship caused by a sudden change of wind condition, leads to failure of positioning. On the basis of the simulations, for a DP system with PD control only, squall A, even happening in a very short time, can lead to the failure of positioning if the wind speed exceeds more than a certain degree of the designed value. Besides, the ship will stay in its maximum position and not return to its original position when suffering from squall B. WFF can decrease the ship's maximum displacement only with a short measurement interval. Adding integral control to the DP system can also achieve the ship staying in its allowable zone but bring severe destabilization. In addition, fluctuating wind in squall does not add extra adverse effects to the performance of DP system, except causing more small destabilizations when suffering squall B. Therefore, squall can affect the performance of DP system in different ways. Some negative effects can be decreased by adding other controllers or tuning gains of controllers. But it may bring another negative effects on the system especially when suffering from different kinds of squalls.

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