

The Need of the Revision of Passenger Ships' Stability Criterion on Account of Turning

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ABSTRACT: The angle of heel on account of turning is one of the mandatory stability criteria for passenger ships. Formula used for calculations of this criterion contained in the International Code on Intact Stability [13] is criticized at present. Agendas of the Sub-committee on Ship Design and Construction (SDC) for the first (2014) and the second (2015) sessions contain the item on revision of this criterion and corresponding regulation. The paper presents some shortcomings of the criterion. Turning tests of a freely maneuvering model of a passenger ship have been executed aiming at gathering data for the future discussion and its facilitation. The paper presents results of the tests together with preliminary conclusions that confirm the need of the revision of the regulation and put forward concerns on application of such values as initial metacentric height (GMo) and righting lever curve ($GZ(\varphi)$) calculated for a ship laying still for calculation of a ship's heel caused by turn.

1 INTRODUCTION AND MOTIVATION

The Sub-committee on Stability and Load Lines and on Fishing Vessels Safety (SLF) completed the work on revision of the International Code on Intact Stability in 2008 [13]. The Code was adopted by Resolution MSC.267(85) on 4th December 2008. Part A of this Code became mandatory on 1st July 2010 via corresponding amendments to SOLAS and Load Lines conventions. At present the Sub-committee on Ship Design and Construction (SDC) has been working on the 2nd Generation Intact Stability Criteria - for example [2], [4], [8].

One of the mandatory stability criterion contained in the 2008 IS Code is special criterion for passenger ships that takes into account an angle of heel in turns. The phenomenon and its effects on the safety of a ship from the stability point of view are widely explained in the literature, for example in [6]. According to the

framework for 2nd Generation Intact Stability Criteria [1] this criterion is classified as deterministic performance based criterion.

The purpose of this criterion is to prevent passenger ships (and other if the criterion has been applied – for example container ships) from a scenario that may be described in following points. Such scenario could be easily presented using TRIPOD method [7].

- 1 The ship sails with the service speed.
- 2 There is a need of immediate turn to avoid a collision or obstacle.
- 3 The rudder has been laid.
- 4 The ship enters into turn and large angle of heel occurs.
- 5 The heel causes cargo shift or another phenomena increasing the angle of heel.
- 6 The heel transits into capsizing.

Some sources claim that the sequence of events presented above might be a cause of the capsizing of the passenger ship Sewol in South Korean's waters in April 2014¹.

“As of 17 April, the ROK Coast Guard has concluded that an unreasonably sudden turn to starboard, made between 8:48 and 8:49 a.m. (KST), was the cause of the capsizing. According to the Coast Guard, the sudden turn caused the cargo to shift to the left, causing the ship to experience an incline and to eventually become unmanageable for the crew. The existence of the sudden turn has been confirmed by the analysis of the ship's Automatic Identification System data. The crew of the ferry has agreed that the main cause was the sudden turn. Experts such as Lee Sang-yun, a professor and head of the environment/maritime technology institute of the Pukyong National University, have also agreed”.

The corresponding text of the regulation related to this phenomenon ([13], Part A, Chapter 3, regulation 3.1.2) is quoted below.

“In addition², the angle of heel on account of turning shall not exceed 10° when calculated using the following formula:

$$M_R = 0.2 \cdot \frac{v_o^2}{L_{WL}} \cdot \Delta \cdot \left(KG - \frac{d}{2} \right) \quad (1)$$

where:

M_R – heeling moment [kNm],
 v_o – service speed [m/s],
 L_{WL} – length of ship at waterline [m],
 Δ – displacement [t],
 d – mean draught [m],
 KG – height of the centre of gravity above baseline [m]”.

This regulation may be expressed by the formula (2).

$$\varphi_R \leq 10^\circ \quad (2)$$

where:

φ_R – angle of heel produced by the heeling moment M_R .

The coefficient 0.2 in formula (1) is the result of the assumption that radius of the turning circle R is equal to five lengths of a ship at waterline L_{WL} (actually it conflicts with the standards for manoeuvrability adopted by resolution MSC.137(76), what may be perceived as another issue for consideration):

$$R = 5 L_{WL} \Rightarrow \frac{1}{R} = 0.2 \cdot \frac{1}{L_{WL}}$$

It shall be stressed that the formula (1) given in the 2008 IS Code defines the method of calculation of the

heeling moment on account of turning M_R but a method of calculation of the angle of heel due to turning φ_R is not defined there. It may be seen as a kind of a shortcoming in the 2008 IS Code – there is no final formula for the angle of heel which is the criterion.

The formula expressing the criterion for the angle of heel in turns - formula (1) - has been criticized by IMO. It has been recognized that this formula is unsatisfactory and needs to be amended. A number of different issues have been identified which require to be addressed [3]. The most important from the author's perspective are listed below:

- 1 The criterion requires the use of the **simplicistic prescriptive** formula for the heeling moment due to turning.
- 2 Maximum permitted angle of heel stipulated by the regulation relates to the angle occurring in the steady state of the turn while the maximum heel occurs at the first stage of the turn and its value is considerably higher than this in steady state.
- 3 The formula employed in the regulation does not take into account the varying turning ability of different vessels which strongly affects the magnitude of the heeling moment and hence the resulting angle of heel. This would pose a significant hazard to the safety of the personnel onboard, as well as to the ship itself.
- 4 **It is not clear in 2008 IS Code what formula or method shall be used for calculation of the angle of heel which actually is the criterion.**

There are two methods of calculation of the angle of heel φ_R used in practice. The first one is by comparison of the heeling lever $l_R(\varphi)$ with righting lever $GZ(\varphi)$ – Figure 1.

$$l_R(\varphi) = \frac{M_R}{\Delta \cdot g} \cdot \cos(\varphi)$$

where:

M_R – heeling moment [kNm],
 Δ – displacement [t],
 g – acceleration due to gravity [m/s²].

$$l_R(\varphi_R) = GZ(\varphi_R)$$

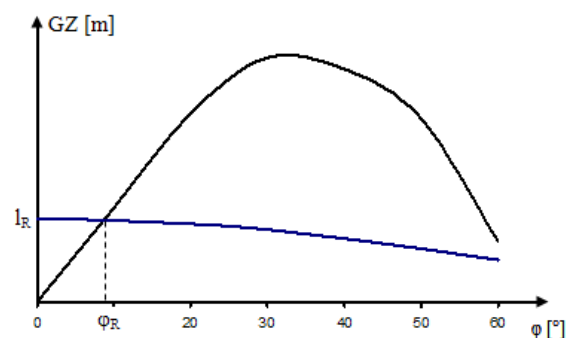


Figure 1. Angle of heel determined using GZ curve

The second method (widely used in stability calculations) is derived as a simplification of the first one. This method uses initial metacentric height GM . It is presented by formula (3).

¹ http://en.wikipedia.org/wiki/Sinking_of_the_MV_Sewol. As the investigation has not been completed till now this quotation shall not be read as the final conclusion regarding the causes of the accident.

² In addition to general criteria given in Part A, Chapter 2, regulation 2.2 and 2.3.

$$\operatorname{tg}(\varphi_R) = \frac{M_R}{\Delta \cdot g \cdot GM} \quad (3)$$

It shall be also noted that in the view of the framework developed by SLF 51 [1] where the “trio”: criterion, standard, regulation were defined as:

- criterion is a procedure, an algorithm or a formula used for judgment on likelihood of failure;
- standard is a boundary separating acceptable and unacceptable likelihood of failure;
- regulation is a specification of a relationship between a standard and a value produced by a criterion;

and in order to make the procedure unambiguous the final form of the corresponding regulation shall be written as follows:

$$\varphi_R = \text{formula} \leq \text{standard} \quad (4)$$

In ship design and ship operation both above mentioned methods use values $GZ(\varphi)$ and GM_0 calculated for static conditions – for the ship laying still. However, in reality the submerged part of the hull is being flown round by water during turning manoeuvre. Therefore actual hydrodynamic pressure distribution in turn is different from the static one. This creates the situation where the restoring moment and metacentric height in turn may differ from these calculated for the ship laying still. This may question approach described in the Figure 1 and by formula (3) and delivers another issue for the consideration of acceptability of the existing regulation.

There has been a substantial amount of literature published on intact ship stability. However, at the same time it is hard to find many studies on the effect of ship's forward speed on restoring moment and in particular initial metacentric height. Furthermore, there are examples of reports supporting the necessity of the research in this field – for example [12] where one may read: *“A quite strange behavior was observed at the standard turning circle test ending with a pull-out. The maximum roll angle was about 28° and when the rudder was put amidships for the pull-out, the yaw rate and roll angle were first decreased as expected, but then increased as speed was picked up. The reason for this unstable behavior was not obvious”*.

Extensive discussions at IMO are expected before any decision concerning amendments to Part A of the 2008 IS Code, regulation 3.1.2 might be taken. The author of this paper decided to execute an experiment – model tests of the turning manoeuvre. Several trials with the use of a freely manoeuvring model of a passenger ship have been executed in Ilawa Ship-handling Research and Training Centre in Poland. The purpose of the experiment was to contribute to the work of SDC Sub-committee by submission a sample of experimental results in order to facilitate

future discussions. In particular, this paper aims at addressing the issue of the effect of forward speed in turn on initial metacentric height as an additional argument (not discussed by IMO till now) for the need of revision of above mentioned criterion.

2 DESCRIPTION OF THE EXPERIMENT

The model tests were performed on Silm Lake in July 2013. The model of a passenger ship that was used for the experiment (scale 1:16) is shown in the pictures presented in Figure 2. Main particulars of the model and Body Lines are presented below.

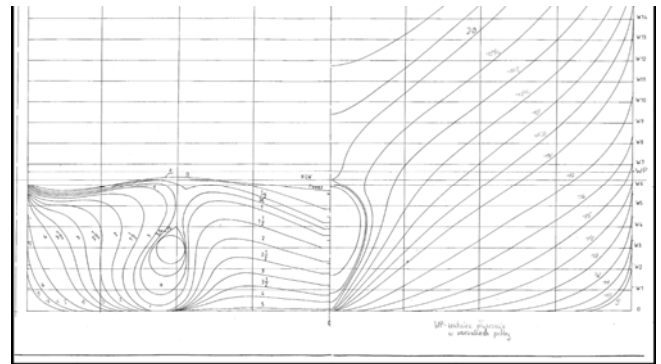
Main particulars

LWL = 11.529 m

B = 1.78 m

Block coefficient = 0.687

Body Lines



a) general view

b) last preparations before the tests

Figure 2. The model used for the tests

The experiment consisted of three stages described in Table 1. The first stage aimed at finding hydrostatic data of the model in the loading condition as prepared for the experiment: the mass (Δ) and the height of the metacentre point above Base Line (KM). The second stage aimed at finding initial metacentric height for the model laying still (GM_0) and the height of the centre of gravity above Base Line (KG). The last stage aimed at measuring the model's position, trajectory and angle of heel versus time caused by laying the rudder. The weather during the experiment was calm – there was no influence of the wind and waves on the results of the measurement.

Table 1. Stages of the experiment

Stage	Description	Measured values	Outcome	No of trials
1.	Drafts measurement	Fore, Aft, Mean Drafts; specific density of the water.	Volume of displacement, mass of the model, height of the metacentre point.	1
2.	Inclining tests	Static angle of heel produced by shifting of the known mass.	Initial metacentric height in standstill (GM ₀); height of the centre of gravity above Base Line.	7
3.	Turning tests	Model's geographical position, rudder deflection, angle of heel – all parameters versus time. circle	Model's trajectory, speed, radius of the turning – all parameters versus time.	7 ³

A 2-dimensional inclination sensor IS 2A xx P20 with voltage interface was used for the purpose of the measurement of the angle of heel. According to the manufacturer's information technical parameters of the device are as follows: data resolution (at zero point) is ± 0.01 [deg] and calibration accuracy is ± 0.3 [deg]. Furthermore the accuracy of the measurement of the geographical position of the antenna $x=x(t)$ and $y=y(t)$ in the area of Silm Lake is ± 0.03 [m]. The frequency of measurement was 0.1 [s] (ten readings per second).

Following parameters of the model that were necessary for the third stage were calculated as the result of the stages no 1 and 2:

$$d = 0.425 \text{ m}; \Delta = 5.43 \text{ t}; GM_0 = 0.296 \text{ m}; KG = 0.804 \text{ m}.$$

The results of one trial (as an example for the third stage of the experiment) are shown in figures 3 and 4 – Full Ahead, rudder 34 [deg] to Port Side. Finally, the experiment gave seven sets of such data. Table 2 contains summary of seven trials – together with some preliminary calculations.

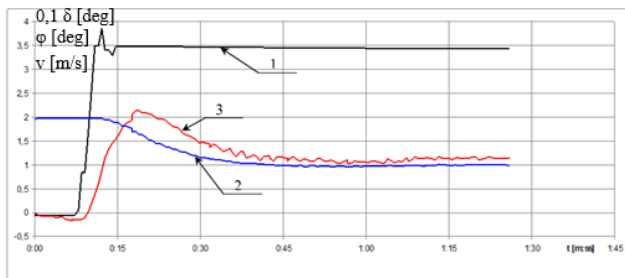


Figure 3. Rudder angle δ (1), speed v (2) and angle of heel φ (3) versus time t (test: 1.1.F/34/PS_1)

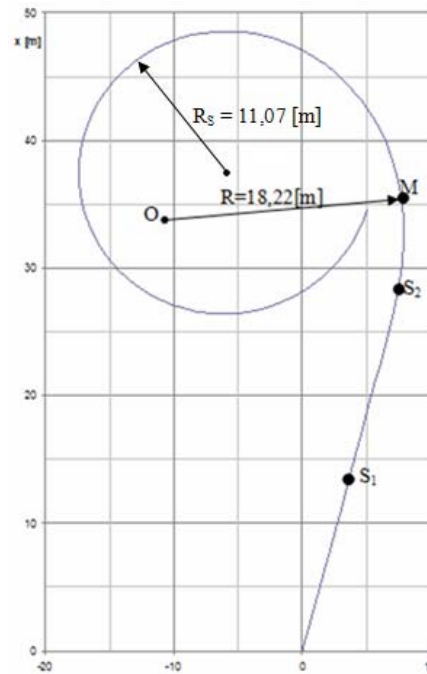


Figure 4. Trajectory of the model during the test (test: 1.1.F/34/PS_1)

Point S_1 in the Figure 4 corresponds to time when the rudder started to move to PS, point S_2 corresponds to time when the rudder angle reached 34 degrees to PS. Point M corresponds to the time when the angle of heel reached its maximum. At that moment the radius of the circulation was R and the centre of turning was in point O . R_s is an average radius of the turn in steady stage.

3 DISCUSSION OF THE RESULTS

Having measured geographical position of the model and the angle of heel versus time and consequently having noticed the steady stage of the turn it was possible to derive other parameters corresponding to the steady stage of the turn: average angle of heel φ_s , average ship speed v_s and average radius R_s .

On the other hand having measured by inclining tests the initial metacentric height GM_0 for the model laying still it was possible to calculate an angle of heel that should be expected in the steady stage of the turn (φ_c) according to the theory hidden behind formula used in the 2008 IS Code. Formula (5) should be used for this purpose.

³ Actually ten trials were performed. Due to a human element three of them have been neglected – there was not possible to determine initial stable angle of heel at the moment when the rudder started to move. Such trial that has been neglected is shown in the Figure 3.

$$\operatorname{tg}(\varphi_C) = \frac{v_S^2}{g \cdot R_S \cdot GM_o} \left(KG - \frac{d}{2} \right) \quad (5)$$

Furthermore Formula (5) may be used for calculation of the angle of heel that was observed in steady stage of the turning (φ_S).

$$\operatorname{tg}(\varphi_S) = \frac{v_S^2}{g \cdot R_S \cdot GM_S} \left(KG - \frac{d}{2} \right) \quad (6)$$

Consequently:

$$GM_S = \frac{v_S^2}{g \cdot R_S \cdot \operatorname{tg}(\varphi_S)} \left(KG - \frac{d}{2} \right) \quad (6a)$$

GMs used in formula (6) answers the question:

- what value of initial metacentric height produces calculated angle of heel equal to measured angle of heel in steady stage of the turn using the theory hidden behind formula used in the 2008 IS Code?

After appropriate mathematical considerations in formulas (5) and (6) we obtain:

$$\frac{GM_S}{GM_o} = \frac{\operatorname{tg}(\varphi_C)}{\operatorname{tg}(\varphi_S)} \approx \frac{\varphi_C}{\varphi_S} = \alpha \quad (7)$$

If the coefficient α in formula (7) was equal 1 it would mean that initial metacentric height observed during steady stage of the turn is equal to initial metacentric height observed for the model laying still and consequently the theory hidden behind the criterion works well in practice.

Table 2 contains the results of measurements in the third stage of the experiment together with results of calculations of parameters and coefficients that could be discussed in the context of the angle of heel due to turn. Following abbreviations have been used in the description of one trial: 1.1 – number of the trial; F/H – the setting of the screw revolutions (Full/Half); 25/33/35 – rudder setting in degrees; SB/PS – starboard/portside.

Table 2. Results of the turning tests and results of preliminary calculations

Parameter	Description of the trial							
	1.2.F35.S	1.3.F35.S	1.4.H25.S	1.6.H35.S	2.2.F35.S	2.3.F33.P	2.4.F35.P	Average
v_o	1.90	1.87	1.47	1.64	1.89	1.91	1.89	
v_S	0.95	0.92	0.73	0.85	0.95	0.82	0.81	
R_S	11.09	11.18	11.15	11.06	11.32	8.89	8.44	
φ_S	1.37	1.29	0.82	1.23	1.43	1.41	1.31	
φ_{Max}	2.68	2.61	1.45	2.06	2.49	2.78	2.40	
φ_C	0.96	0.89	0.55	0.77	0.92	0.88	0.90	
φ_S / φ_C	1.43	1.45	1.49	1.60	1.55	1.60	1.46	1.51
GM_S	0.205	0.203	0.201	0.183	0.193	0.185	0.205	0.197
v_S / v_o	0.50	0.49	0.50	0.52	0.50	0.43	0.43	
R_S / L_{WL}	0.96	0.97	0.97	0.96	0.98	0.77	0.73	
$\varphi_{Max} / \varphi_C$	2.79	2.93	2.64	2.68	2.71	3.16	2.67	2.80
$\varphi_{Max} / \varphi_S$	1.96	2.02	1.77	1.67	1.74	1.97	1.83	1.85
$\alpha = GM_S / GM_o$	0.69	0.68	0.68	0.62	0.65	0.63	0.69	0.66

Following abbreviations have been used in the Table 2:

- v_o – observed initial speed of the model [m/s];
- v_S – average speed of the model observed at the steady stage of a turn [m/s];
- R_S – average radius of the turning trajectory observed at the steady stage of a turn [m];
- φ_S – average angle of the heel observed at the steady stage of a turn [deg];
- φ_{Max} – maximum angle of the heel observed during turning test [deg];
- φ_C – angle of the heel calculated at the steady stage of a turn using formula (5) [deg];
- GM_S – initial metacentric height calculated using formula (6a) [m];
- L_{WL} – length of the model on the waterline [m];
- GM_o – initial metacentric height determined by inclining test for the model laying still [m].

Parameters calculated in the Table 2 (shadowed fields) contain following information:

- 1 Average angle of the heel observed at the steady stage of a turn is in more or less 150% larger then angle of heel calculated using formula (5). At the same time coefficient α calculated with formula (7) is equal about 0.66. It means that significant

reduction of initial metacentric height was observed at steady stage of the turn in comparison with model laying still.

- 2 Reduction of the model's speed in steady stage of the turn in comparison with the initial speed was about 50% for starboard turn and about 43 % for the turn to port.
- 3 Average radius of the turning trajectory observed at the steady stage of a turn was about 0.97% of the length of the model on the waterline in turn to starboard and about 75% in turn to port.
- 4 Maximum observed angle of heel was 280% larger in average then calculated using formula (5) and 180% larger in average then angle of the heel observed at the steady stage of a turn.

Additionally it is worth to mention that the angle of heel calculated according to IMO regulation using formulas (1) and (3) for model's main particulars is equal 0.73 [deg]. This means that IMO regulation underestimates both: angle of heel observed at the steady stage of the turn and maximum angle of heel.

Observation 1 above is in contrary to conclusions reported by Taylan [11] deduced on the base of experiments made by Sobolev [9] and Obrastsov [10]

– “increasing forward speed alone improves intact statical ship stability most of the time”. It proves that more research is needed to explain the phenomena related to effect of forward speed on intact stability, in particular what parameters play the main role in this phenomenon.

Coefficient α in the Table 2 (being less than 1) contains the information that the model in turn due to water flow and specific water pressure distribution on the hull is more vulnerable to heeling moments than in stillness. It proves that formulas (1) and (3) or method shown in the Figure 1 shall not be used for the purpose of stability assessment of a ship in turn. The pressure distribution on a hull surface in turn shall be investigated in more detailed way and the results of the investigation should be properly applied. *It is very important finding from this experiment.* Coefficient α may be interpreted as “reduction of initial metacentric height GM” during turning manoeuvre.

From the author’s perspective at present there are three possible options how to conduct the discussion at IMO aiming at revision of the current criterion.

- 1 Development of a tuning coefficient that will take into account a number of parameters affecting maximum angle of heel in turn. This tuning coefficient might replace “0.2” contained in current regulation. This approach was proposed in Polish document submitted in November 2013 to the first session of SDC Sub-committee which was held in January 2014 [5]. It requires a lot of model and full scale tests and is very conservative one. Furthermore it is not physically based. Eventually this coefficient may occur to be ship dependent what would make the approach complicated in practice.
- 2 Development of a method for calculation of the “reduced initial metacentric height in steady turn” and consequently to keep the formula for calculation as it is - provided that coefficient “0.2” would be deleted and “real” radius of the turning circle would be used. This radius could be obtained from model or full scale tests, computer simulations or an analysis of existing ships similar to this under consideration. The maximum angle of heel could be assumed to be twice of this in steady stage as it may be derived using simplified method of the calculation of so called “dynamical angle of heel”⁴ ($\varphi_D \approx 2 \varphi_C$).
- 3 Development of a physically based method of calculation of maximum angle of heel in turn (which is dynamical one) that takes into account energy balance of all heeling moments acting on a ship at the first stage of the turn, particularly moment produced by rudder, inertia moment (produced by centrifugal force), dumping moment and restoring moment. Physically based method means here a method that takes also into account hydrodynamic pressure distribution acting on submerged part of the ship sailing with forward speed in turn.

⁴ This coefficient equals 1,85 in the case of the model used for the experiment. It is lower than theoretical one (which is 2,00) due to rudder effect, added mass effects, dumping and other effects.

The third option (being robust one) is the most desirable as it is in line with performance based approach to the second generation intact stability criteria. But on the other hand it requires solving a number of very complex problems related to hydrodynamic phenomena which up to now have not been adequately investigated and understood. For this reason one should not expect this option could be applied in the nearest amendments to 2008 IS Code.

4 CONCLUSIONS

Seven turning tests have been executed using a model of a passenger ferry. Angles of heel have been measured together with ship’s speed and trajectory as a function of time. The test results may be summarized as follows:

- 1 It is hard to find studies on the effect of ship’s forward speed on restoring moment. This effect is not taken into account in mathematical models and computer codes used for ships’ rolling simulations.
- 2 A ship in turn is more vulnerable to heeling moments than the ship laying still. It is the result of different pressure distribution on the surface of the hull in these two cases.
- 3 Initial metacentric height G_{M0} calculated for the ship laying still does not describe the stiffness of the ship in turn with acceptable adequacy.
- 4 The findings from the model tests show that formula (1) contained in the 2008 IS Code together with formula (3) commonly used in practice shall not be used for stability assessment of a ship in turn as they underestimate actual angle of heel (maximum I transient and average in steady stage of the turn).
- 5 Three possible options how to proceed further at IMO in order to revise current regulation were indicated.
- 6 Tuning of the coefficient used in formula (1) may be temporary way out but this is very conservative approach and may open new problems like ship-dependence. Development of the method for “reduction of GM” caused by turning is another possibility. This approach (if applied) shall be perceived also as a temporary one.
- 7 A number of additional model and full scale tests followed by extensive discussion are needed before revision of the corresponding part of the 2008 IS Code may be agreed. Eventual modification of this criterion should preferably avoid application of G_{M0} or $GZ(\varphi)$ values calculated for a ship laying still. The influence of the forward speed on these parameters may be crucial in this case.

Mathematical models of ships’ rolling and consequently computer codes used for simulation do not take into account the influence of forward speed on restoring moments. Very well known problems with validation of mathematical models and computer codes may be reduced to some extent in the future if forward speed is properly taken into account in restoring moments calculation.

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