Effect of Transom Stern Bottom Profile Form on Stern Wave Resistance - An Experimental Study -

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When a ship with a wide immersed transom stern runs on a deeper draft than its design draft, forward-oriented wave breaking often occurs just behind the transom stern. The phenomenon accompanies large momentum loss and accordingly large hull resistance. The bottom profile form of the transom stern is one of the most important factors which affect the phenomenon, though not so much attention must has been paid to the part in many ships just by the reason that the part is only a limited local part of a hull. In this paper, model tests on typical bottom profile forms are conducted at first and then the effect of the bottom profile form on stern wave resistance is discussed based on the results of the model tests. As a result, characteristics and amount of the effect and the relation between the bottom profile form and the stern wave resistance are clarified.

Keywords: Transom Stern Bottom Profile Form, Stern Wave Resistance, Model Test, Small Model Ships

List of Symbols

- $B$: hull breadth (m)
- $B_m$: mean breadth of immersed transom stern end plane (m)
- $C_f = R_f / (0.5 \rho S v_0^2)$: frictional resistance coefficient (-)
- $C_r = R_r / (0.5 \rho B_m T v_0^3)$: residual resistance coefficient (-)
- $\delta C_r = C_r - C_r^c$
- $C_r^c$: of M.S.NO.170a0a,af
- $F_r = v_0 / (g L_w)\rho^2$: Froude number (-)
- $F_r = v_0 / (g I)\rho^2$: Froude number based on $I$ (-)
- $g$: gravitational acceleration (m/s$^2$)
- $I$: stern end immersion at rest (m)
- $I_r$: real stern end immersion at running with ship speed $v_0$ (m)
- $L_w$: load water line length (m)
- $R_s = v_0 L_w / \nu$: Reynolds number (-)
- $R_f$: frictional resistance (N)
- $R_{ts}$: total resistance of a full scale ship (N)
- $S$: wetted surface area (m$^2$)
- $v_0$: ship speed (m/s)
- $v_1 = v_0 (1 + 2 g (I - I_r) / v_0^3)^{0.5}$: flow velocity just out of boundary layer at stern end (m/s)
- $\delta$: boundary layer thickness at stern end (m)
- $\theta$: slope angle of bottom profile at stern end (deg)
- $\nu$: kinematic viscosity of water (m$^2$/s)
- $\rho$: density of water (kg/m$^3$)
- $swfb$: abbreviation of 'forward-oriented wave breaking'
- TKM: abbreviation of 'transverse metacentric height'

1. Introduction

Recent container ships have rather wide immersed transom sterns to keep necessary transverse stability. When such a ship runs on a deeper draft than its design draft, forward-oriented wave breaking (abbreviated swfb hereafter)** with high turbulent intensity often occurs just behind the transom stern. The
swbf accompanies large momentum loss and accordingly large hull resistance. To prevent or decrease the phenomenon is, therefore, important for energy saving for such ships. Some studies for the purpose including those on a special stern form and some appendages have been conducted by one of the authors. However, one of the most fundamental studies to be conducted is certainly that to optimize the conventional transom stern form. In this paper, we have taken up the stern bottom profile form as a component of transom stern form to be studied, importance of which our studies on transom stern have suggested.

The stern bottom profile is decided in the earliest stage of hull form design. In design of the stern bottom profile form, the following two restrictions at least have to be taken into consideration. One is that by TKM and another is that by propeller vibratory forces. As shown in Fig.1, the lowest point at the stern end P1 should be lower than a point PA to keep necessary TKM, and the point P2 on the hull just above a propeller should be higher than a point PB to lower the propeller vibratory force under a required level. As a result, heights of two points P1 and P2 are decided. If no other restrictions are given, we can choose any form, for example, such as Profiles I, II and III shown in Fig.1 for the bottom profile between the two points. This part must has been regarded not so important for hull resistance just by the reason that it is only a limited local part of a hull, and the simplest form like Profile II must has been adopted for many ships.

As a similar study to our present study, studies on the effect of stern flaps or stern wedges on hull resistance have been reported. The mechanism through which the stern flaps or stern wedges reduce the hull resistance is, however, not yet completely clarified.

In the following, we compare three fundamental stern bottom profile forms, 'concave', 'flat' and 'convex' by model tests at first. Then, based on the results of the model tests, we try to clarify characteristics and amount of the effect of stern bottom profile form on stern wave resistance and the relation between the stern bottom profile form and the stern wave resistance.

2. Outline of Model Tests

2.1 Model Tests

Resistance test, stern wave height measurement and stern wave surface observation have been conducted on three model ships with different stern bottom profile forms.

2.2 Measurement Apparatus

2.2.1 Model Tank

The circulating water channel of Hyogo University of Teacher Education has been used for the model tests. Particulars of the model tank are shown in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length(m)</td>
<td>1.2</td>
</tr>
<tr>
<td>Breadth(m)</td>
<td>0.3</td>
</tr>
<tr>
<td>Water depth(m)</td>
<td>0.2</td>
</tr>
<tr>
<td>Flow speed(m/s)</td>
<td>0-0.7</td>
</tr>
</tbody>
</table>

Table 1 Particulars of model tank.

Item with mark * shows size of observation part

2.2.2 Measurement or Observation Instruments

(1) Resistance

A new instrument has been designed and manufactured to measure the resistance of small model ships in the small model tank.

Outline of the instrument is shown in Fig.2. A model ship (△) is fastened to a floating frame (⊙). The floating frame (⊙) has four floats (▽) (outer diameter × outer depth = 190mm × 220mm) in four water tanks(●) (inner diameter × inner depth = 250mm × 220mm). The water tanks (●) are out of the model tank and on a fixed main frame (●). The floating frame (⊙) is connected to the fixed main frame (●) with two pantographs (●) and is free to move fore-and-aft and up-and-down. An aimed draft of the model ship (△)
can be realized by adjusting amount of the water in the water tanks \( \bullet \). The floating frame \( \blacklozenge \) is, on the other hand, connected to a load cell \( \square \) on the fixed main frame \( \blacklozenge \) with a wire \( \blacklozenge \). The load cell \( \square \) can measure resistance of the model ship \( \ast \) up to 50gf. Total resistance of each of the model ships measured in the present study has ranged from 4 to 14gf.

Most of the weight of the model ship and the floating frame is supported by the buoyancy of the four floats and not by the displacement of the model ship.

The model ship, therefore, can be called "a captured model ship" and not "a floating model ship".

Results of calibration for the instrument are shown in Fig.3. Fig.3 shows measurement accuracy is 0 to +2.5%.

(2) Waves

Wave heights have been measured with a servo motor type water level meter. Stern wave surface has been recorded with a digital video camera.

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![Fig.2 Resistance measurement instrument.](image)

![Fig.3 Results of calibration for resistance measurement instrument.](image)

![Fig.4 Hull lines of model ships](image)
(3) Flow velocity
Flow velocity has been measured with a propeller type flow velocity meter with a 3 mm-diameter propeller.

2.3 Model Ships
Stern end immersion at rest $I$ and slope angle of bottom profile at the stern end $\theta_e$ are important components of transom stern form for stern waves. Because these two components are considered almost to determine the height and phase of the stern wave. On the other hand, $\theta_e$ can be regarded as an index to represent the stern bottom profile form. We, therefore, have designed and manufactured three model ships with different $\theta_e$ and with same $I$. M.S.Name 'convex' ($\theta_e = -4.76$ deg.), 'flat' ($\theta_e = 0$ deg.) and 'convex' ($\theta_e = +4.76$ deg.) to grasp the effect of the stern bottom profile form. Minus sign of $\theta_e$ means aft-end down and plus sign aft-end up.

Table 2 Particulars of model ships.

<table>
<thead>
<tr>
<th>M.S.NO.</th>
<th>M.S. Name</th>
<th>$\theta_e$ (deg.)</th>
<th>$L_{wl}$ (m)</th>
<th>$B$ (m)</th>
<th>$d$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>170a-5a.af</td>
<td>'convex'</td>
<td>-4.76</td>
<td>0.32</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>170a0a.af</td>
<td>'flat'</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>170a+5a.af</td>
<td>'convex'</td>
<td>4.76</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$I$ (m)$=0.005$, $B_r$(m)$=0.092$ for all model ships.

![Fig.5 Photographs of model ships.](image)

Table 3 Test condition.

<table>
<thead>
<tr>
<th>M.S.NO.</th>
<th>M.S. Name</th>
<th>$d$ (m)</th>
<th>$I$ (m)</th>
<th>$v \times 10^6$ (m$^3$)</th>
<th>$S \times 10^6$ (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>170a-5a.af</td>
<td>'convex'</td>
<td>0.01</td>
<td>0.005</td>
<td>1.642</td>
<td>3.718</td>
</tr>
<tr>
<td>170a0a.af</td>
<td>'flat'</td>
<td>0.01</td>
<td>0.005</td>
<td>2.223</td>
<td>3.881</td>
</tr>
<tr>
<td>170a+5a.af</td>
<td>'convex'</td>
<td>0.01</td>
<td>0.005</td>
<td>2.520</td>
<td>3.944</td>
</tr>
</tbody>
</table>

$v_r$(m/s) 0.4878 0.6091 0.6877 0.8139
$F_w$ 2.203 2.752 3.107 3.677

Fig.6 Flow velocity distribution in model tank without a model ship.
3.2 Relation between Stern Bottom Profile Form and Stern Wave Resistance

3.2.1 Relation between Stern Waves and Stern Wave Resistance

Figs. 9-1, 9-2 and 9-3 show comparison of stern wave surface photographs of the three model ships taken at $F_{rt} = 2.752, 3.107$ and 3.677 respectively at the resistance tests.

Fig 10 shows stern wave height comparison among the three model ships at $F_{rt} = 2.752, 3.107$ and 3.677. The stern wave heights have been measured at the points with 5mm intervals in the hull-center-line plane. The measurement has been conducted separately from the resistance test.

At the lower ship speed range of $F_{rt} < 3.1$, by comparing Figs. 9-1, 9-2 and Fig.10 with Figs.7, we can see that the stern wave surface just behind the stern end is smoother in case of lower stern wave resistance ('concave'). The smoother wave surface is considered to mean that amount of the swbf is smaller.

At the higher ship speed range of $F_{rt} > 3.1$, the relation is different. The stern wave surface of 'concave' is very smooth and almost same as that of 'flat' at $F_{rt} = 3.677$ as shown in Figs.9-3 and 10. This is considered to show that amount of the swbf and also

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Fig.7 Resistance test results.

Fig.8 is derived from Fig.7 and shows the relation between $\theta_r$ and $\delta C_r$. $\delta C_r$ is residual resistance coefficient difference from that of 'flat' and can be considered stern wave resistance coefficient difference due to the stern bottom profile form difference from that of 'flat', because the same fore-body form is adopted for the three model ships.

Fig. 8 Relation between slope angle of bottom profile at stern end and stern wave resistance.

The relation between $\theta_r$ and $\delta C_r$ seen in Figs.7 and 8 is not so simple, and the relation can be summarized as follows: At the lowest ship speed $F_{rt} = 2.203$. stern wave resistance of 'concave' is smallest and there is no difference of stern wave resistance between 'flat' and 'convex'. At $F_{rt} = 2.752$, decrease of $\theta_r$ causes decrease of stern wave resistance. At the higher ship speed range of $F_{rt} > 3.1$, stern wave resistance of 'flat' is smallest.

Fig.9-1 Stern wave surface ($F_{rt} = 2.752$).
resistance due to the phenomenon are very small on both of the model ships. The stern wave resistance of 'concave' is, however, larger than that of 'flat' as shown in Figs. 7 and 8.

This stern wave resistance difference between 'concave' and 'flat' is considered due to the difference of another component of stern waves, the remaining following waves. The remaining following waves mean the waves which do not break just behind the stern end and propagates afterwards as free waves. The remaining following wave height of 'concave' can be estimated to be larger than that of 'flat', though this tendency is not so clear in the measured wave heights shown in Fig. 10.

3.2.2 Relation between Real Stern End Immersion and Stern Wave Resistance

To grasp the relation between the swbf and the stern wave resistance quantitatively, we introduce the real stern end immersion \( I_r \) defined in Fig. 11. \( I_r \) is the thickness of water layer by the water broken by the swbf. Therefore, \( I_r \) can be regarded as an index to represent amount of the swbf.

\( I_r \), on the other hand, determines the flow velocity just out of the boundary layer at the stern end \( v_1 \) according to the following relation:

\[
v_1 = v_0 (1 + 2g(I - I_r)/v_0^2)^{0.5}
\]

(1)

This \( v_1 \) is one of the important factors which determine the swbf. The relation (1) shows that larger \( I_r \) causes lower \( v_1 \). Lower \( v_1 \) generates heavier swbf. So, it can also be said that \( I_r \) determines the swbf. Fig. 12 shows \( I_r \) of the three model ships. in non-dimensional form. read from the record with a

![Fig. 10 Measured stern wave heights.](image)
resistance at $F_{r1} = 2.752$. Fig. 13 also confirms that the swbf largely controls stern wave resistance at the lower ship speed range

At the higher ship speed range of $F_{r1} > 3.1$, the relation is different. Smaller $I_r$ does not necessarily bring smaller stern wave resistance. The reason has been explained in 3.2.1.

3.2.3 Relation between Stern Bottom Profile Form and Real Stern End Immersion

Fig. 12 shows that $I_r$ increases with decrease of ship speed on a stern. This confirms that the swbf is easier to occur at the lower ship speed\textsuperscript{1213). Fig. 12 also shows that $I_r$ largely depends on the stern bottom profile form and is smallest on 'concave' and largest on 'convex' at a $F_{r1}$

Position of the first trough (or the trough just in front of the first peak) of stern wave is estimated to be just at the stern end in case of 'flat', that is aft from the stern end in case of 'concave' and that is fore from the stern end in case of 'convex'. This tendency can be seen in Fig 10. This tendency is considered to cause the widest room between the first stern wave peak and the stern end for the water broken by the swbf of 'concave' and the narrowest room for the water of 'convex'. This size of the room is considered to be another factor to determine the value of $I_r$ besides the amount of the swbf, the main factor.

The smallest $I_r$ of 'concave' and the largest $I_r$ of 'convex' at a $F_{r1}$ are, therefore, considered to be due to the largest room of 'concave' and the smallest room of 'convex'.

$I_r$ depends on amount of the swbf and also on the stern bottom profile form as shown in Fig. 12. On the other hand, $I_r$ and not the stern bottom profile form has a close co-relation with the stern wave resistance at the lower ship speed as shown in Fig. 13. These data are considered to show that $I_r$ relates with the stern wave resistance as a cause of the swbf rather than as a result of the swbf, where $I_r$ is a result of the swbf and is also a cause of the swbf as explained in 3.2.2.

3.3 Relative Amount of the Effect in Hull Resistance

To check whether above obtained effect of stern bottom profile form is significant in amount in the powering of a full scale ship, ratio of the stern wave resistance difference due stern bottom profile form difference to total resistance is estimated on a full-scale ship
(S.NO. CA. Full-2 condition in ref. 3): $L_{wl} = 269.2m$, $I = 1.8m$, $d = 12.0m$ at $F_1 = 0.25$, $F_{r1} = 3.057$. Stern wave resistance coefficient difference from that of 'flat' $\delta C_r$ at this $F_{r1}$ is read -0.023 for 'concave' and 0.084 for 'convex' from Fig.7. $\delta R_r$ for the full-scale ship can be calculated based on these $\delta C_r$. Obtained $\delta R_r/R_t$ are -3.9% for 'concave' and +14% for 'convex', where $R_t$ is total resistance of the full-scale ship. The latter value seems a little larger. However, it can be said at least that the amount of the effect is significant.

4. Conclusions

The following have been clarified by comparing three fundamental stern bottom profile forms: 'concave', 'convex' and 'flat' by model tests:

1) Effect of the transom-stern bottom-profile form:
The concave stern bottom profile causes the lowest stern wave resistance at the lower ship speed range of $F_{r1} < 3.1$. The flat stern bottom profile causes the smallest stern wave resistance at the higher ship speed range of $F_{r1} > 3.1$.

2) Relation between Stern Bottom Profile Form and Stern Wave Resistance:

1) At the lower ship speed range of $F_{r1} < 3.1$, the stern bottom profile form controls the stern wave resistance mainly by controlling the real stern end immersion $I_r$.

2) At the higher ship speed range of $F_{r1} > 3.1$, the stern bottom profile form controls the stern wave resistance mainly by controlling the remaining following wave height.

3) The concave stern bottom profile causes the smallest real stern end immersion $I_r$, which is important at the lower ship speed range. The flat stern bottom profile causes the lowest remaining following wave height which is important at the higher ship speed range.

3) Relative amount of the effect in hull resistance:
Amount of the effect of the stern bottom form change is estimated to be significant in the powering for a full-scale ship.

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References


Discussion

【Discussion】田村喜也

コンテナ船のトランスランス船尾の形状やその抵抗に就いて、理論、実験の両面から精力的に研究に取り組み、特に成功を収めていることに関して敬意を表します。

今回は小型模型船を用い、船尾プロファイル形状の相違による微視抵抗の抵抗差を巧みに検出し、その形状の影響に就いて考察した結果を御発表になりました。

以下、質問をさせて頂きます。

（1）模型船にTurbulence Stimulatorを取り付けられましたが、その取付け位置や寸法等はどうのようにしてお決めになったのでしょうか。

（2）同実験の水面は、小型模型のない場合では、高さ差や波が生ずるということを知りつつも波高を計測の際にこれらの影響はどのように修正されたのでしょうか。

（3）本論文の（1）式では、文献1）に示されていている式の "F" の代わりに "F - I" を使用していますが、この詳細について御説明下さい。

（4）実際のコンテナ船型については通常、Fig.1に示されているように、船尾のプロファイルは船尾端から船首に向かって下降しとなっております。このような船型に対して、Concaveのプロファイルを採用するにあたって、問題はないと考えて良いでしょうか。

（5）今後はScantling draftを対象に試験を行っておりますが、もっと使用頻度が高いDesign draftでは、F-1が更に大きくなると思います。このような船に対してConcaveのプロファイルを採用するにあたって、問題はないと考えて良いでしょうか。

【Author's Reply】

ご討論ありがとうございます。

（1）同実験での小型模型船の実験に豊富な実績を持つFELの推奨を基に決めました。取りつけ位置ss91/2近くは通常取りつけている位置です。詳細な検討を行っていないが、模型寸法が小さい事を考慮して、高さ1.5mmは多少低く、間隔7.5mmは多少狭いでした。と伺っております。

（2）ご指摘の通り沿流水槽での波高計測は容易ではありません。今回の波高計測は次の方法で行っております：1）模型船なしの状態で流速を計測して、水面がフラットとなるように（観測部最上部にある水平な波制御装置の下面と水面が同一面内に入るように）水槽の水位を調整する。この時の水面を波高の基準面（波高 = 0）とし、波高計測位置の水位を計測する（ほとんど水深でした）。2）次に模型船を設置して、模型船の排水量分だけ、水槽の水を抜く。この状態で波高を計測する。波高計の精度は最大 +/−0.1mm、波高計測前後の基準面の高さに最大 +/−0.3mmの誤差が認められました。波高計測結果には、このような誤差が入っております。

（3）現状では、Iを推定することが出来ないので、文献1）では船尾端直後の前方への波崩れが発生する直前の流れ、すなわちI = 0の状態の流れを推定しました。それを基にして、前方への波崩れがどのように起こるかを検討しました。そこで、文献1）では、I = 0として船尾端での流速を推定しました。

Iは前方への波崩れの結果ではありませんが、Iは（1）式に従って船尾端での流速を左側します。従って、これを通じてIは前方への波崩れを左右する原因にあります。

今回実験でIの値を計測しましたので分かっております。そこで、前方への波崩れが発生する直前の流れを推定する時には、船尾端での流速についてはこのIの影響を入れることにして（1）式を採用しました。近似度を一つ上げたと良い得るかと思います。

（4）船尾波を決めめる船尾形状の主要なI（船尾波の波高を決める）とθ（船尾波の位相と波高を決めめる）であると言う前提で今回の研究を行っております。このような前提に立って、今回の単純な形状の模型の実験結果でも、実船のIとθの検討に使えるのではないかと考えております。

しかし、今回の実験では拘束模型船を使用しておりますので、船尾端形状の違いがトランスラントに及ぼす影響が実験結果に入っておりません。これは、別途調べる必要があります。ご指摘の前方へ向かって下降する形状は、この論文の記号を除けば、θ = + degと定義できます。

（5）ご指摘の通り、Design draftのF-1はScantling draftのF-1よりも高くなります。従って、Design draftで最もθとScantling draftで最もθが異なる可能性は十分あります。船状態の船尾波による抵抗、更にθの航走抵抗等を考慮して最適のθを選ぶことになるかと思います。

【Discussion】岡本淳

本研究は船尾端の形状、浸水、抵抗の関係について、有用な情報を示しておき評価できると思います。

次の点について補足説明してください。
（1）Fig.2 の計測装置と同流水槽・水路との関係
（2）同じく、水タンク④との関係
（3）Fig.12. および 13 にて、F₁ = 3.677 に於ける concave’ の点 Α は 0 のように見えるが
（4）F₁ > 3.1 にて stern-wave resistance の相関が
変わるのは、3 次元影響ではないか。Stern end 幅が異
なるとこの F₁ も異なるのではなかろうか。

【Author’s Reply】
ご討論有難う御座います。
（1）および（2）
1) Fig.2 の抵抗計測装置の「固定枠」⑤、それに固
定されている 4 つの「水槽」⑥、そして「固定枠」⑨
に縫った「筏」⑦、これらは同流水槽のどことも繋
がっておらず、同流水槽とは独立した装置です。「固定
枠」⑨はキャスター付きで移動可能ですが、計測時
には「同流水槽」を同時に押して跨ぐ形で両者の中心線を
合わせて固定されます。
2) 「固定枠」②は、「筏」⑦を仲立ちとして、次のよう
な形で、「同流水槽」に浮かんだ（正確に言えば、浮かん
ではおられませんが）「模型亀」①に繋がっております。
4 つの「筏」⑦の付いた「筏」⑦を、上記の 4 つ
の「水槽」⑥に浮かべます。この「筏」⑦に、「同流水
槽」に浮かんだ「模型船」①を個縫します。
「模型船」①付の「筏」⑦の重量は「筏」⑦に付
いている「浮き」⑨の浮力及び「模型船」①の浮力
で支えます。そこで、模型船の喫水は 4 つの「水槽」
の水位（水量）を変えて調整します。この 4 つの
「水槽」③の中で、右舷側の 2 個および左舷側の 2 個
は、それぞれ水管で連結されております。
この「筏」⑦を 2 つ並べた「バンクグラフ」①で「固定
枠」⑦に連結します。これにより、「模型船」①は同
流水槽の中で上下および前後には動けることになりま
す。一方で、この「筏」⑦を「ワイア」⑥で「固定
枠」⑦上の「検力計」⑥に繋ぎます。同流水中の水を
流すと、この「検力計」⑥が「ワイア」⑥で「模型
船」①付の「筏」⑦を引っ張る事になり、その引っ
張り力すなわち模型船の抵抗を計測します。

（3）
Fig.12 の F₁ = 3.677 の Α 点の縦軸 J / J の値は 0
です。ちなみに F₁ = 3.677 の Ω 点の縦軸 J / J の値
も 0 です。「convex’（□）一点線の傾向から、Δ 点も
Ω 点も 3.677 より小さな F₁ で J が 0 になると推察
されます。その J が 0 となる F₁ の最小点を計測は
していないので、「flat’（○）実線および concave’（△）
破線の右端の形を、'convex’（□）一点線の形状を参
考にして、Fig.12 に示すような形にしたものです。
Fig.13 の F₁ = 3.677 の Ω 点の縦軸 δC の値は図
示の通り正です。Ω と Δ はこの F₁ で、両者共に J =
0 ですが、船尾流速抵抗はΩよりも Δ の方が大きいと
言う結果になっています。

（4）そうかもしれません。今後の検討課題とさせて頂
きます。