Theoretical Study on Rotation of Doubly Layered Torque Balance Cable

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Abstract - Remotely Operated Vehicle (ROV) uses long tether cable for power supply and signal communication between a ROV and its support vessel. However there have been many accidents on this tether cable, such as kink and disconnection caused by rotation of the cable.

The tether cable is usually a torque balance type one with its strength members of inner/outer layer braided reverse direction each other. However, even if a torque balance of the cable is perfect, cable rotation occurs in most ROVs while paying in/out of a tether cable into the ocean.

In this research, calculation method of strand track of a tether cable bent on a sheave was established, and the reason of the cable rotation was found to be the change of track length caused by bending of the tether cable on sheave, applying this calculation method. Comparison of the calculated results and measured data of JAMSTEC ROVs shows this calculation method to be very good to explain the rotation phenomena.

I. INTRODUCTION

Although a very long tether cable is widely used for an operation of ROV for underwater development, many troubles on cable have been ocurring in most ROVs in the world such as kink, birdcaging or disconnection. The Japan Marine Science and Technology Center (JAMSTEC) had faced this problem since the start of the operation of 3,300m class ROV “Dolphin 3K” (1985). Although JAMSTEC is now operating 11,000m class ROV “KAIKO,” this cable rotation problem had never been clarified.

In the development of the “KAIKO,” it was presumed that the fleet angle had influenced cable rotation phenomenon. Then a ram-type heave compensator with almost 0 degree of fleet angle was developed. However, the rotation of tether cable was still about 1 time per 100m, and the effect of the effort was not found [1, 2]. Although the number of cable rotation of the newer KAIKO No.2 cable decreased to 1/4 of the former one, the mechanism of this phenomenon has never been understood. Therefore the same problem must be inevitable when fabricating a long new cable.

Looking these phenomena, the authors obtained a new hypothesis that the reason of cable rotation must be a change of strand track while the cable is bent on sheaves from the straight condition. This hypothesis can only be proven by obtaining theoretically precise formulation to describe the strand tracks, and the authors had made the effort.

A. Cable Rotation Phenomena

Cable rotation described in this paper does not mean the rotation by residual torsion just after the fabrication. Fig.1 and Fig.2 are the examples of measured data of cable rotation to be discussed here. A weight with a Flux-gate compass is hanged at the bottom end of a cable, and the rotation number is counted while paying in/out of the cable into the sea. The rotation per unit cable length did not change by descending/ascending speed. The interesting point is the rotation of the weight while paying in of a tether cable. Any residual torsion, the cable may have, must be purged out when the cable is paying in, and the torque must be balanced all over the cable. Yet, the cable rotates by constant numbers per length while paying in from the sea. In addition to the number of rotation, the direction reverses while

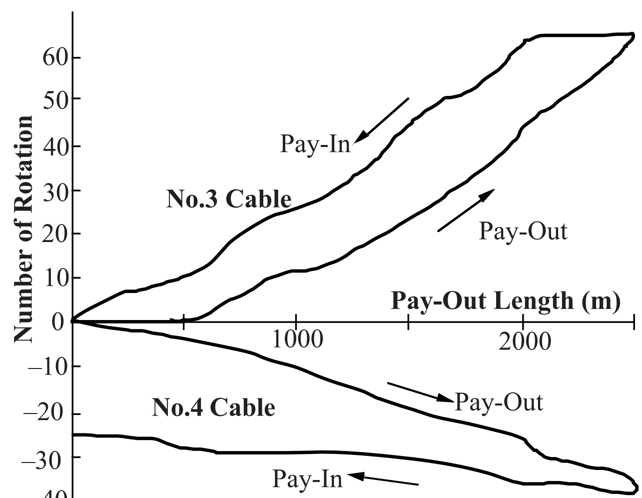

Fig.1 Measured Results of Cable Rotation of ROV Dolphin 3K No.3 and No.4 Cables

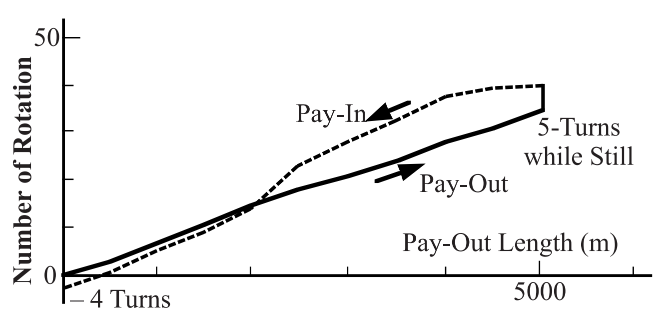

Fig.2 Measured Result of Cable Rotation of ROV KAIKO No.1 Cable

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paying in and out.

This is a very strange phenomenon because there seems no unbalance torque to rotate the cable at all. There had been no clue to tackle and solve this problem, and only trial and error by fabricating and testing new cables had been continued.

B. Slip Restriction of Strands on Cable Rotation

Cable rotation seemed to be caused not either by cable or sheave only, but to be related to the interaction of cable and sheave. Especially, the outer strands and inner strands seemed to be slipping each other on the sheave. If they are really slipping, the rotation must occur. So, an adhesive stripe was introduced in between outer and inner strands of KAIKO No.1 cable in order to restrict the slip if any as shown in Fig.3. The test was done using a machine shown in Fig.4, where rotations of indication bars were measured. Comparison of the test results of a conventional cable and a cable with slip restriction are shown in Fig.5, and it shows the effect of slip restriction very clearly. The rotation of a conventional cable is about 1 rotation per 100m (15deg/4m = 360deg/100m) which is almost the same as shown in Fig.2, whereas, the cable with slip restriction would

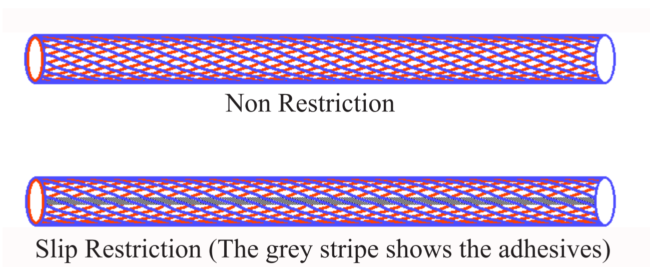

Fig.3 Slip Restriction on Strands

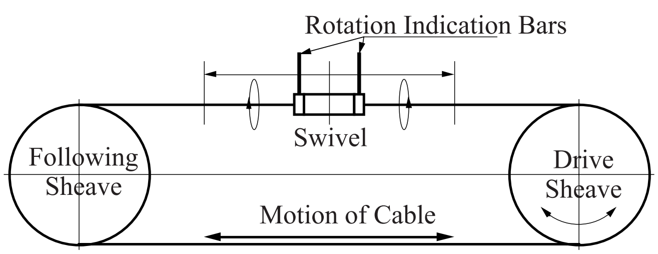

Fig.4 In-House Cable Rotation Measurement System

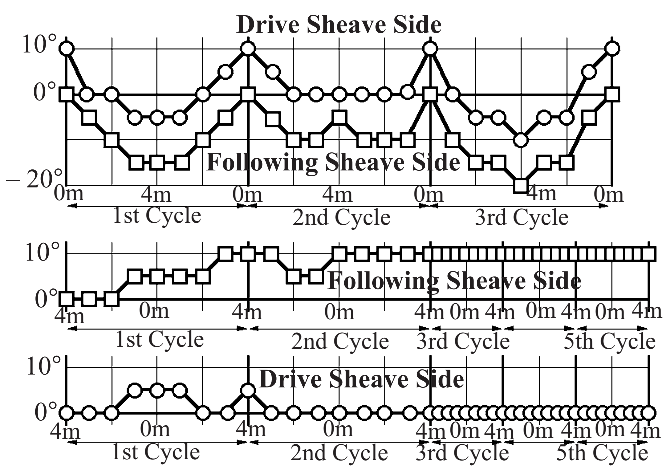

Fig.5 Results and Comparison of Slip Restriction Effect

not rotate.

This test gave the authors a clear idea on the cable rotation mechanism and the authors carried out further research for the purpose of clarifying this mechanism theoretically.

II. FUNDAMENTAL MECHANISM

Strands of doubly layered torque balance cable are braided reverse direction each other so that the torque of cable including power lines and signal lines is balanced. These strands in each layer are not contact one another, but are twisted around the cable core with adequate gap for flexibility of bending and twisting of the cable.

The tracks of these strands are helicoids with constant gradient in the straight state. However, when the cable is bent on a sheave, the each strand tends to go to inner part of bending to fill up the gap, and the gap at the outer part of bending becomes larger. The strand which contacts with the neighboring strands at the inner part of bending is called as “Contact strand,” and the non-contact strand is called as “Free strand” in this paper. There must be a specific point on the strand where the contact strand detaches with the neighboring strands to become free strand. This point is called “Detaching point.”

The track of the strand thus become different from that of the straight state, and the length of the strand at one pitch length must become different from that of the straight state also.

These differences must occur at both the inner and outer strands. The authors think that these differences destroy the torque balance of the cable and make the cable rotate.

So, the authors have started the effort to establish the calculation method of strands track of a tether cable bent on sheaves at first, and then to clarify the mechanism of cable rotation phenomena.

III. NOMENCLATURE

R : Radius of sheave pitch circle
p : Strand pitch
D : Outer diameter of strand
r : Radius of helical coil from centerline
N : Number of strands
$\boldsymbol{b}$: Binormal vector of strands and the components
$\mathbf{N}$: Normal vector on curved surface of strands helicoidal coil and the components
$\boldsymbol{n}$: Normal vector of strands track
$\boldsymbol{t}$: Tangential vector of strands track and the components
g : Cable rotation
v : Angle from binormal vector to cable center
L : Strand/cable length ratio
w : Radius of curvature of strands ($1/w$: curvature)
q : Coordinate angle of helical coil for strand
f : Phase angle from sheave center
$*$: Vector product operator
Δ : Difference between L_s
subscript “i” : Inner layer
subscript “o” : Outer layer
subscript “s” : Cable of straight condition

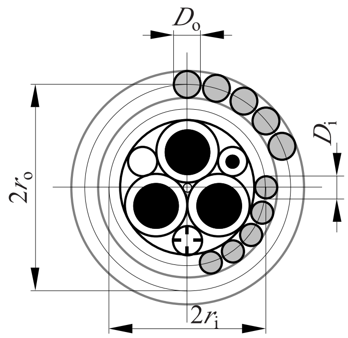

Fig.6 Cross Section of Cable and Symbols

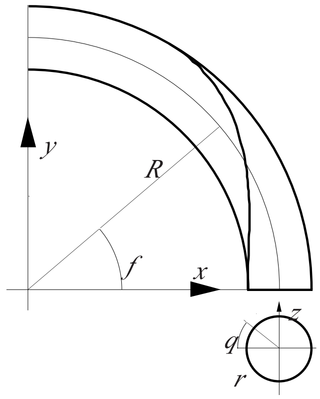

Fig.7 Coordinate System of the Strand

subscript "c" : Cable of curved condition by bending on a sheave

Fig.6 shows the cross section of cable and symbols, and Fig.7 shows the coordinate system.

IV. TRACK CALCULATION[3, 4, 5]

In the coordinate system shown in Fig.7, coordinates of a strand center are express as follow:

$$(x, y, z) = \{(R - r\cos q)\cos f, (R - r\cos q)\sin f, r\sin q\} \quad (4.1)$$

By use of the infinitesimal increment of strand arc length ds = (dx^2 + dy^2 + dz^2)$^{1/2}$, the components of the tangential vector $\boldsymbol{t}$ = (x_t, y_t, z_t) = (dx/ds, dy/ds, dz/ds) are given as follows:

$$\mathrm{d}x/\mathrm{d}s = \{r\sin q\cos f - (R - r\cos q)\sin f(\mathrm{d}f/\mathrm{d}q)\}/A$$
$$\mathrm{d}y/\mathrm{d}s = \{r\sin q\sin f + (R - r\cos q)\cos f(\mathrm{d}f/\mathrm{d}q)\}/A$$
$$\mathrm{d}z/\mathrm{d}s = r\cos q/A. \quad (4.2)$$

where $A = \{r^2 + (R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)^2\}^{1/2}$.

Their second order differentials d^2x/ds^2, d^2y/ds^2, d^2z/ds^2, are given as follow:

$$\mathrm{d}^2x/\mathrm{d}s^2 = \{r^3\cos q\cos f - 2r^3\sin q\sin f(\mathrm{d}f/\mathrm{d}q) + r\cos f(R - r\cos q)(R\cos q - 2r)(\mathrm{d}f/\mathrm{d}q)^2 - r\sin q\sin f(R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)^3 - \cos f(R - r\cos q)^3(\mathrm{d}f/\mathrm{d}q)^4 - r^2\sin f(R - r\cos q)(\mathrm{d}^2f/\mathrm{d}q^2) - \sin q\cos f(R - r\cos q)^3(\mathrm{d}f/\mathrm{d}q)^4\}/B$$
$$\mathrm{d}^2y/\mathrm{d}s^2 = \{r^3\cos q\sin f + 2r^3\sin q\cos f(\mathrm{d}f/\mathrm{d}q) + r\sin f(R - r\cos q)(R\cos q - 2r)(\mathrm{d}f/\mathrm{d}q)^2 + r\sin q\cos f(R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)^3 - \sin f(R - r\cos q)^3(\mathrm{d}f/\mathrm{d}q)^4 + r^2\cos f(R - r\cos q)(\mathrm{d}^2f/\mathrm{d}q^2) - \sin q\sin f(R - r\cos q)^3(\mathrm{d}f/\mathrm{d}q)^4\}/B$$
$$\mathrm{d}^2z/\mathrm{d}s^2 = \{-r^3\sin q - r\cos q(R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)(\mathrm{d}^2f/\mathrm{d}q^2) - rR\sin q\,(R - r\cos q)(\mathrm{d}f/\mathrm{d}q)^2\}/B \quad (4.3)$$

where $B = \{r^2 + (R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)^2\}^2$.

Curvature $1/w$ of this strand track becomes as follows:

$$1/w = \{(\mathrm{d}^2x/\mathrm{d}s^2)^2 + (\mathrm{d}^2y/\mathrm{d}s^2)^2 + (\mathrm{d}^2z/\mathrm{d}s^2)^2\}^{1/2}.$$

The normal vector of this surface of the envelope of track is a unit vector shown as follows:

$$\boldsymbol{N} = (x_N, y_N, z_N) = (\cos q\cos f, \cos q\sin f, -\sin q)$$

A. Free Strand

Free strand received tension only and does not receive external forces from the neighboring strands. So, the direction of normal vector of strand $\boldsymbol{n}$ = (d^2x/ds^2, d^2y/ds^2, d^2z/ds^2) and that of $\boldsymbol{N}$ are the same. Thus, the scalar product $w\boldsymbol{nN}$ is as follows:

$$w(r\cos q\cos f\mathrm{d}^2x/\mathrm{d}s^2 + r\cos q\sin f\mathrm{d}^2y/\mathrm{d}s^2 - r\sin q\mathrm{d}^2z/\mathrm{d}s^2) = 1 \quad (4.4)$$

This equation becomes the following one, and is modified to eq. (4.5):

$$\{r^2 + (R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)^2\}[r(R - r\cos q)(\mathrm{d}^2f/\mathrm{d}q^2) + \sin q\{2r^2 + (R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)^2\}(\mathrm{d}f/\mathrm{d}q)]^2 = 0$$
$$r(R - r\cos q)(\mathrm{d}^2f/\mathrm{d}q^2) + \sin q\{2r^2 + (R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)^2\}(\mathrm{d}f/\mathrm{d}q) = 0 \quad (4.5)$$

This second order differential equation can be transformed to the following first order differential equation.

$$\mathrm{d}f/\mathrm{d}q = \pm\, r/(R - r\cos q)\{Kr^2(R - r\cos q)^2 - 1\}^{1/2}. \quad (4.6)$$

where K is an integration constant given by any boundary condition. This equation can be integrated easily, and a free strand track is determined.

B. Contact Strand

If a strand contacts with neighboring strands, the value of scalar product $w\boldsymbol{nN}$ is not 1, and eq. (4.6) cannot be applied. Instead, the contact point of the strand is calculated by the following procedure:

The tangential and normal vectors at any point $\boldsymbol{P}_I$ of a strand are easily calculated using its coordinate (q, f). The binormal vector bI at the point can also be calculated as follow by using the $\boldsymbol{N}_I$ and $\boldsymbol{t}_I$.

$$\boldsymbol{b}_I = \boldsymbol{N}_I * \boldsymbol{t}_I = (x_{bI}, y_{bI}, z_{bI})$$
$$x_{bI} = \{r\sin f + (R - r\cos q)\sin q\cos f(\mathrm{d}f/\mathrm{d}q)\}/C$$
$$y_{bI} = \{-r\cos f + (R - r\cos q)\sin q\sin f(\mathrm{d}f/\mathrm{d}q)\}/C$$
$$z_{bI} = (R - r\cos q)\cos q(\mathrm{d}f/\mathrm{d}q)\}/C \quad (4.7)$$

where $C = \{r^2 + (R - r\cos q)^2(\mathrm{d}f/\mathrm{d}q)^2\}^{1/2}$.

The contact point of neighboring strand $\boldsymbol{P}_{II}(x_{II}, y_{II}, z_{II})$ is on the $\boldsymbol{N}_I$-$\boldsymbol{b}_I$ plane, and is at a distance (r) (Radius of helical coil from centerline) apart from the cable center and at a distance (D) from $\boldsymbol{P}_I$. The contact point $\boldsymbol{P}_{II}(x_{II}, y_{II}, z_{II})$ is calculated as follows:

$$(x_{II}, y_{II}, z_{II}) = (x_I, y_I, z_I) + D\cos\nu_I\boldsymbol{b}_I + D\sin\nu_I\boldsymbol{N}_I. \quad (4.8)$$

where the ν_I means an angle from the strand center $\boldsymbol{P}_I$ on the $\boldsymbol{N}_I$-$\boldsymbol{b}_I$ plane to make the distance of $\boldsymbol{P}_{II}$ to the cable center as r as shown in Fig.8.

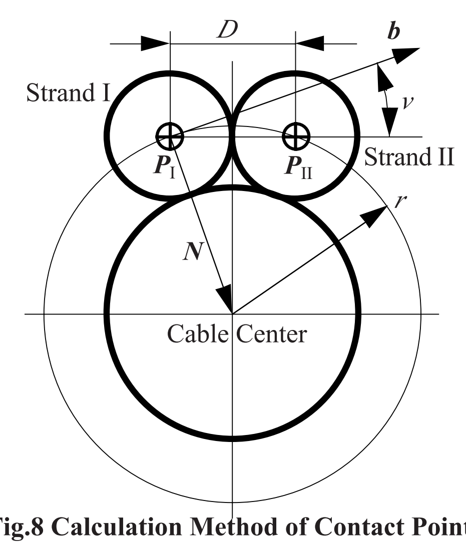

Fig.8 Calculation Method of Contact Point

As $y_{II}/x_{II} = \tan f_{II}$, the ν_I is determined as to satisfy the following equation.

$$(x_{II} - R\cos f_{II})^2 + (y_{II} - R\sin f_{II})^2 + z_{II}^2 = r^2. \tag{4.9}$$

On the other hand, the following equation is also valid on $\boldsymbol{N}_{II}$-$\boldsymbol{b}_{II}$ plane when looking from the $\boldsymbol{P}_{II}$:

$$(x_I, y_I, z_I) = (x_{II}, y_{II}, z_{II}) - D\cos\nu_I \boldsymbol{b}_I - D\sin\nu_I \boldsymbol{N}_I$$
$$= (x_{II}, y_{II}, z_{II}) + D\cos\nu_{II} \boldsymbol{b}_{II} + D\sin\nu_{II} \boldsymbol{N}_{II}.$$

Therefore, $D\cos\nu_I \boldsymbol{b}_I + D\sin\nu_I \boldsymbol{N}_I + D\cos\nu_{II} \boldsymbol{b}_{II} + D\sin\nu_{II} \boldsymbol{N}_{II} = 0$

The tangential vector at $\boldsymbol{P}_{II}$ on the strand II can be calculated by the vector product as:

$\boldsymbol{b}_{II} * \boldsymbol{N}_{II} = \boldsymbol{t}_{II}$.

$$(\cos\nu_I \boldsymbol{b}_I + \sin\nu_I \boldsymbol{N}_I) * \boldsymbol{N}_{II} + \cos\nu_{II} \boldsymbol{t}_{II} = 0. \tag{4.10}$$

where the two tangential vectors $\boldsymbol{t}_{II}$ and $\boldsymbol{t}_I$ are not parallel but skew vectors each other.

Utilizing this equation, the track of "Contact strand" is calculated by the following procedure:

(1) Calculate the contact point $\boldsymbol{Q}(x_{II}, y_{II}, z_{II})$ on the neighboring strand II with an arbitrary point $\boldsymbol{P}_I$ on the strand I.

(2) Calculate the next point $\boldsymbol{P}_{II}$ on the strand I by forwarding the point $\boldsymbol{Q}(x_{II}, y_{II}, z_{II})$ by the phase angle ($= p/R/N_S$). This can be done because each strand has the same configuration and differs by the phase angle.

A track of strand I in contact state can be obtained by repeating the same procedure as shown in Fig.9. In addition to a strand track, two coordinate (q, f)s and inclinations (df/dq)s on the same strand track are obtained.

The most important matter of this calculation is the correctness of the first two points. If the positions of the two points are incorrect, all points calculated hereafter by this method are also incorrect.

Therefore, the following procedure is needed to calculate the first two points correctly:

(1) Define the start point as $(q, f) = (0, 0)$

(2) Set an arbitrary inclination df/dq at the first point (e.g. Strand inclination in the straight state).

(3) Calculate the coordinate and inclination of contact point $\boldsymbol{Q}$ of the start point $\boldsymbol{P}_I$. Then forward the point $\boldsymbol{Q}$ by the phase angle to determine the second point $\boldsymbol{P}_{II}$.

(4) Describe the track between the first point $\boldsymbol{P}_I$ and the second point $\boldsymbol{P}_{II}$ (track of "First section") by a polynomial ($f = \sum a_j q_j$). Since there are four conditions as the two coordinates and two inclinations, the order of polynomial is third with four coefficients.

(5) As the strand track at $q \geq 0$ and $q \leq 0$ are symmetric with respect to the point $q = 0$, the first point $(q, f) = (0, 0)$ must be an inflection point, i.e. the term of second order (the coefficient of the second order differentials) must be zero. By use of this condition, the inclination df/dq at the first point $\boldsymbol{P}_I$ where $(q, f) = (0, 0)$ is determined and the polynomial of strand track is also determined.

(6) The third point $\boldsymbol{P}_{III}$ is determined by forwarding the phase angle from the contact point $\boldsymbol{Q}$ of the second point $\boldsymbol{P}_{II}$, and the track between $\boldsymbol{P}_{II}$ and $\boldsymbol{P}_{III}$ is "Second section." As the coordinates and the inclinations of both ends and second order differential coefficients at the $\boldsymbol{P}_{II}$ are already given, the degree of polynomial is 4th with five coefficients.

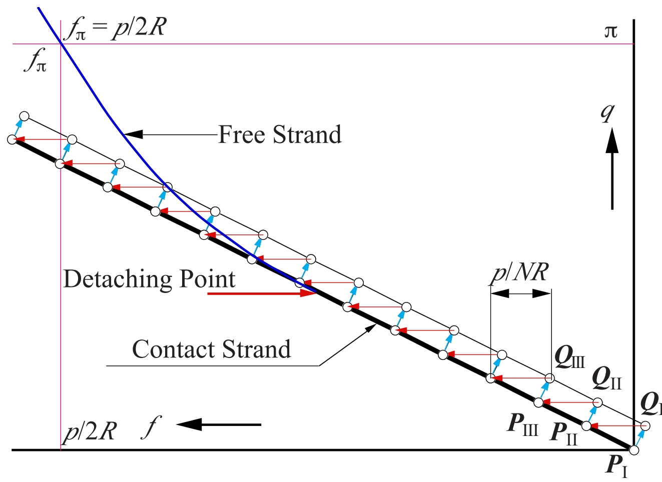

Fig.9 Construction of Strand Track with Contact Strand and Free Strand

(7) Repetition of the procedure (6) gives the track of "Contact strand," however, this procedure certifies only the contact with the neighboring points at the both ends of each section, but does not certify the contact at the middle part of section. So, some modification is required

(8) As for the modification, the track of the first section is expressed by a polynomial of 4th order instead of third order by adding one degree of freedom. Then the second section was aftwarded by the phase angle in order to confirm the contact at the middle part. Twenty points were selected on the first section, and the contact point of each one and its distance were calculated. Then, the coefficient of the 4th order was adjusted so that the square-sum of these distances become minimum. Thus, the track of the first and the second section were determined.

(9) As for the tracks of third section or more, fifth order polynomial was used instead of fourth in order to make close contact at middle part of the section

(10) Hereafter, repeat the procedure (9), and the track of contact strand can be thus obtained.

C. Transition from Contact Strand to Free Strand

As is already mentioned at the "fundamental mechanism", the strand in contact condition at the inner part of bending. This strand goes gradually to the outer part of bending with contact condition, but it becomes a free strand at some specific position, and reach the point of $q = \pi$. At this point of $q = \pi$, the f must be $f = p/2R$, that means the half of the pitch. The pitch length may be different from the original one due to twist of the cable, and the pitch length of twisted cable shall be used if any.

In order to find this detaching point from contact strand to free strand, the following procedure was used (see Fig.9):

(1) The calculation starts from the track of the second section of contact strand, and the track of free strand from the end of the second section shall be calculated. Then the position of the free strand at $q = \pi$ shall be calculated. If this value $f_\pi < p/2R$, then the track of the third section is calculated and the track of the free strand from the end of the third section shall be calculated. This process is repeated

section by section until the $f_\pi > p/2R$

(2) The detaching point must exist on the middle of the latest section, and the point is surveyed so that the $f_\pi = p/2R$. Thus, the track of the strand is finally fixed.

(3) These calculations are done both for inner layer strand and outer layer strand. The lengths of strands of both layers are also calculated

V. NUMBER OF CABLE ROTATION[5]

The strand lengths of the bent cable on a sheave are different from those of straight cable, and this difference must be the origin of the cable rotation. In order to evaluate the number of cable rotation, a new index L of the ratio of strand length to cable length is introduced. For the cable of straight condition, it is written as follows:

$$L_s = (p^2 + 4\pi^2 r^2)^{1/2}/p. \quad (5.1)$$

In the case of the cable bent on a sheave, the new index $L = L_c$ is given as:

$$L_c = l_c/p. \quad (5.2)$$

where l_c is a strand length of one pitch length of cable on a sheave.

These indices mean strand lengths in unit lengths of cable.

When the cable in the straight condition proceeds into a sheave every unit length, the strand enters into the sheave by the length of Ls. However, the length of strand on sheave per unit length of cable is L_c. Most cases, $L_s \neq L_c$ and unbalance of strand length occurs by $\Delta L = L_s - L_c$.

For the cable of doubly layered strands, the unbalance of inner layer is $\Delta L_i = L_{si} - L_{ci}$, and that of outer layer is $\Delta L_o = L_{so} - L_{co}$.

If the differences of ΔL_i and ΔL_o are the same, inner and outer layer may only extend or shrink at the same rate. However, if the ΔL_i is different from ΔL_o, the unbalance of the length of an inner and outer layer occurs, and this unbalance must be absorbed by some way, that means, the cable rotation.

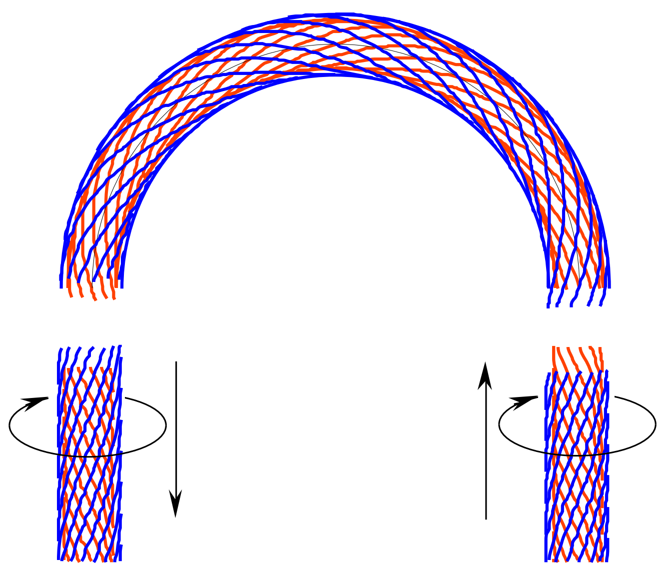

Fig.10 CableRotation at the Entrance and Exit of Sheave
The Difference of Inner and Outer Layers makes
the Cable outside of Sheave rotate.

The cable cannot rotate on a sheave since it is strongly pushed to sheaves by its tension, so the unbalance can be absorbed in the straight part because there are not any restrictions.

The rotation of g per unit length makes the pitch of both outer and inner layers as follow:

$$1/p_o' = 1/p_o + g$$
$$1/p_i' = 1/p_i - g. \quad (5.3)$$

The length difference of the strands between inner and outer layers per unit length of the cable by this rotation g can be calculated as follows:

$L_{si}' = (p_i'^2 + 4\pi^2 r_i^2)^{1/2}/p_i'$: The L_s of inner strand after rotation of g

$L_{so}' = (p_o'^2 + 4\pi^2 r_o^2)^{1/2}/p_o'$: The L_s of outer strand after rotation of g

By the cable rotation of g, the L_s of the inner and outer strand change by ΔL_{si} and ΔL_{so} as follow:

$$\Delta L_{si} = L_{si}' - L_{si} = (L_{si}'^2 - L_{si}^2)/(L_{si}' + L_{si}) \approx (L_{si}'^2 - L_{si}^2)/2L_{si} \approx -4\pi^2 r_i^2 g/p_i L_{si}$$

$$\Delta L_{so} = L_{so}' - L_{so} = (L_{so}'^2 - L_{so}^2)/(L_{so}' + L_{so}) \approx (L_{so}'^2 - L_{so}^2)/2L_{so} \approx +4\pi^2 r_o^2 g/p_o L_{so}$$

In order for the cable to absorb the length difference, the difference $\Delta L_{so} - \Delta L_{si}$ at the cable of straight condition must be equal to that of the bent condition on a sheave, that means, $\Delta L_o - \Delta L_i$. This gives the following equation:

$$\Delta L_o - \Delta L_i = \Delta L_{so} - \Delta L_{si} = 4\pi^2(r_i^2/p_i L_{si} + r_o^2/p_o L_{so})g.$$
$$g = (\Delta L_o - \Delta L_i)/4\pi^2(r_i^2/p_i L_{si} + r_o^2/p_o L_{so}) \quad (5.4)$$

The term of $\Delta L_o - \Delta L_i$ is calculated with $g = 0$ at the start, and a repetition calculation is required so that the same g is used both on $\Delta L_{so} - \Delta L_{si}$ and on $\Delta L_o - \Delta L_i$. Further, the actual rotation becomes $2g$ because the cable of rotation g enters into the sheave with further rotation of g at the entrance to the sheave. Or, while getting off the sheave, the cable releases the rotation g at the exit of the sheave and releases further rotation of g of its own twisting.

VI. JAMSTEC TETHER CABLE DATA AND THE CALCULATION RESULTS

JAMSTEC has been and is now using several long tether cables and their specifications are shown in Table 1. The comparison between the measured rotation data of these cables in the sea and calculated results of them are shown in the same Table 1. The calculated results agree well with measured data except those of the Dolphin 3K-No.4 cable and the KAIKO-No.1 cable (the colored columns). For the cases of good agreement, the strands are steel wire or Kevlar FRP both with exactly round sections as design data. This Kevlar cable has been fabricated by winding the solidified Kevlar strand around the cable core. On the other hand, for the cases of no good agreement, sections are not round shaped, but are like quadrilateral sections as shown in Fig.11. This cable has been fabricated by winding non-solidified Kevlar strand around the cable core, and then it was solidified. The data used for these cases were those before winding around the cable core.

So the cross-sectional shapes were measured using actual

Fig.11 Cross-Section of KAIKO-No.1 Cable
Strands are quadlilateral shapes due to the close contact with each other while they are solidified.

cable samples. But it was nearly impossible to determine the contact point with neighboring strands. Calculations with various contact points were done, and it was found that calculation results agreed with measured data of cable rotation by selecting the contact point appropriately as shown in Table 2. It must be noted that the Dolphin 3K-No.4 cable rotates reverse direction compared with the other cables and this reverse direction of rotation could happen when the contact point or the gap is an appropriate value.

VII. CONCLUSION

The cable rotation phenomena of doubly layered torque balance cable can be explained by the previous description. The cause of cable rotation is summarized as follow:

(1) Each strand of a tether cable has adequate gap between the neighboring strands in order to keep its flexibility.
(2) If a cable is bent on a sheave, each strand tends to go to the inner side of bending to fill-up these gaps under tension. This makes the strand as "Contact Strand."
(3) The contact state of a strand with the neighboring strands ends at the certain point as it goes outer side of bending. Then the track changes to "Free Strand."
(4) The tracks and lengths of the strands change due to the bending, and the lengths of inner and outer strands every unit length of cable become different from those at straight condition of cable.
(5) These differences can only be absorbed by the cable rotation in the straight part.
(6) The cable rotation can be expressed by the eq. (5.4), and the amount is $2g$.

Operation of long tether cable is inevitable for the ocean activities, and the cable rotation must be as small as possible. Torque balance is one of the most important items for the design and fabrication of the cable, but also great attention must be paid to the cable rotation on sheave, utilizing the concept shown in this paper.

VIII. REFERENCES

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Table 2. Recalculation Results of Large Discrepancy Cables

		D-3K No.4	D-3K No.5	KAIKO No.1
Strand Thickness(mm)	Outer L.	1.88	1.76	3.5
	Inner L.	2.28	2.08	4.0
Strand Width(mm)	Outer L.	2.10	2.43	3.5
	Inner L.	2.56	2.92	4.1
Contacting Pitch Rad.(mm)	Outer L.	12.48	12.5	18.35
	Inner L.	10.7	10.9	14.7
Measured Rotation/100m		ab.–1	——	ab.+1
Calculated Rotation/100m		–1.03	+1.47	+1.02

Table 1. Specifications and Measured/Calculated Rotation of JAMSTECs ROV Cables

		D-3K No.3	D-3K No.4	D-3K No.5	KAIKO No.1	KAIKO No.2	Deep Tow No.1	Deep Tow No.2	Hyper-D
Cable Dia.(mm)		30.5	30.3	30.4	44.0	43.7	17.4	17.4	27.7
Strand Pitch(mm)	Outer L.	400	300	282	400	480	125	118	194
	Inner L.	250	245	250	250	380	99	100	173
Strand Dia.(mm)	Outer L.	1.9	2.0	2.2	3.6	3.05	1.84	1.43	1.47
	Inner L.	1.9	2.5	2.5	4.3	4.55	1.46	1.59	2.01
Winding Pitch Rad.(mm)	Outer L.	12.8	12.85	12.9	18.7	18.6	7.78	7.985	12.99
	Inner L.	10.9	10.6	10.55	14.75	14.8	6.13	6.475	11.25
Number of Strands	Outer L.	39	35	30	30	36	24	31	50
	Inner L.	33	24	22	20	19	24	23	32
Pitch Circle Rad. of Sheave(mm)			462		700		477.5		610.8
Measured Rotation/100m		ab.+3	ab.–1	——	ab.+1	ab.+1/4	ab.+0.9	ab.+0.9	——
Calculated Rotation/100m		2.79	4.28	2.81	2.27	0.22	0.79	0.88	0.46

The Name "D-3K" is "Dolphin 3K" and "Hyper D" is "Hyper Dolphin."