Measuring Submarine Optical Cable Tension from Cable Vibration

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A new tension measuring system for submarine cables utilizing the lateral vibration frequency of cables to calculate their tension with sufficient accuracy, has been proposed. Cable bend stiffness, the pay out/recovery velocity of cables and response time of the measurement have been examined on land and out-at-sea. The new tension meter thus developed is a handy system consisting of an optical vibration detector, conventional filter and an F/V converter and recorder, and covers a wide range of tension from 10kN up to more than 100 kN within an error of 10%. In conclusion, the new system was found to improve the reliability of submarine cable pay-out and recovery operations as well as to offer a safer and more accurate tension measuring method, in general, for elongated substances.

Key Words ; Vibration, Measurement, Submarine Optical Cable, Tension Meter, Cable Ship

1. Preface

Recently, research on submarine transmission systems utilizing optical fibers has been progressing rapidly worldwide. N.T.T. has been conducting out-at-sea experiments on submarine optical transmission systems since January, 1983.

While ideal in many ways, optical fibers are small in diameter and easily broken compared with conventional copper cables. The lifetime of optical fibers is directly affected by the mechanical characteristics of optical fiber material, S_1O_2 . Thus for optical fibers, the lower the stress and the shorter the duration of stress the better in terms of lifetime. Fiber stress is directly linked to cable tension occurring during cable laying and recovery and also to the residue cable tension once it is laid on the sea bed. It is important to recognize the precise applied tension pattern to predict cable lifetime and improve laying and recovery methods so that the applied tension can be controlled to within a desirable level. For this purpose, it is necessary to measure, record and compile the values of cable tension in actual conditions. To date, however, precise tension measurements for the more durable conventional submarine cables have not been considered important with the result that highly accurate cable tension meters have not been developed. Now that submarine optical cables, with their more fragile nature, have come into focus, accurate cable tension meters are required.

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This paper describes the development of a highly accurate cable tension meter utilizing the relationship between the lateral vibration frequency of cables and their tension. The new tension meter reported here is a handy system consisting of an optical vibration detector, conventional filter and an F/V converter and recorder, and covers a wide range of tension from 10kN up to more than 100 kN within an error of 10 %.

2. Requirements of a submarine optical cable tension meter

Table 1. Design objectives of the submarine optical cable tension meter

Item	Target	Conventional Tension meter
Range	0 ~ 120 kN {0 ~ 12.2 tf}	0 ~ 300 kN {0 ~ 30.6 tf}
Error	Less than 10%	Around 50% (Low tension) range
Response	Less than 1s	Around 3s (Low tension) range
Cable	Submarine optical cable, etc.	All kinds
Structure	Handy type	Permanently fixed on board

The major requirements of the new tension meter are given in Table 1. With the smaller optical cable diameter, bulk and weight are considerably reduced making it possible for cable pay-out and recovery to be carried out from smaller ships and commissioned ships. Thus, any optical cable tension meter must be compact, handy and portable.

3. Existing tension meter and its problems

A diagram of the existing cable tension meter on board NTT's cable ship, the KUROSHIO MARU is given in figure 1. Here, the cable is supported by the fulcrum with angles θ_1 and θ_2 with load W on the load cell. Thus cable tension T can be expressed as

$$T = W / (\sin \theta_1 + \sin \theta_2) \dots \dots \dots (1)$$

Allowance must be made for tension measurement error due to the following:

(1) Error due to θ_1 or θ_2 shifts

θ_1 , θ_2 change with cable tension and bending rigidity as well as with pitching and rolling of the ship.

Actually, θ_1 , θ_2 constantly alter by 5° , theoretically producing a measurement error of 50%.

(2) Error due to mechanical friction

Existing tension meters are a part of the hold back gear (DO/HB) which controls pay out of cables on the drum-type cable engine with the cable gripping wheel of the DO/HB used as the fulcrum. Such tension meters weigh several kilonewtons causing a rather big inertia force to be generated according to the ship motion and loaded on the tension meter's load cell which, together with the mechanical friction from the suspension of the fulcrum, produces a large measurement

Fig.1. Existing cable tension meter

Fig.2. An example of measurement when using the existing tension meter

error. Data from the existing tension meter without cable on it indicates an error of 10 to 20 kN for this tension meter, as shown in figure 2.

4. New theory for measuring tension

4-1 The theory and its error rate

The relationship between the tension of string and its lateral vibration frequency can be utilized to measure submarine cable tension. First of all, cable bending rigidity, the pay out/recovery velocity of cables and response time of the measurement should be examined.

4.1.1 Bending rigidity

Natural frequency f of the bar suspended by both ends under tension can be expressed as follows using f_1 to represent the frequency caused by bend stiffness, and f_2 to represent the frequency caused by tension, both of which are natural frequencies of systems where only bend stiffness or tension generates a reaction force against vibration:

$$f = \sqrt{f_1^2 + f_2^2} \dots \dots \dots (2)$$

f_1 and f_2 can be written as follows:

$$f_1 = \frac{n^2 \pi}{2L^2} \sqrt{\frac{EI}{\rho a}} \dots \dots \dots (3)$$

$$f_2 = \frac{n}{2L} \sqrt{\frac{T}{\rho a}} \dots \dots \dots (4)$$

where,

L = suspended cable span;

n = order;

EI = bending rigidity;

ρa = mass per unit length;

T = cable tension;

From these equations the fundamental frequency f_0 of the cable under tension T can be derived as:

$$f_0 = \sqrt{\frac{\pi^2 EI}{4L^4 \rho a} + \frac{1}{4L^2} \frac{T}{\rho a}} \dots \dots \dots (5)$$

and cable tension can be expressed as:

$$T = 4L^2 \rho a f_0^2 - \left(\frac{\pi}{L}\right)^2 EI \dots \dots \dots (6)$$

According to equation (6), cable tension can be derived by measuring f_0 when cable specifications and suspending span are given.

The 2nd term of equation (6) depends on the bending rigidity. Some values are given in Fig.3. For example, to keep measurement error within 10% eliminating the need for compensation, a cable span of more than 3m is required.

4.1.2 Error caused by cable running.

Tension measurement error caused by cable running can be expressed as:

$$\frac{\partial^2 y}{\partial t^2} = c^2 \frac{\partial^2 y}{\partial x^2} \dots \dots \dots (7)$$

where

- ξ = axis fixed along with the string;
- y = transversal displacement of the string;
- c = propagation speed of wave in the cable;

Here, $c = \sqrt{T/\rho a}$ The solution to the equation (7) can be written as follows using arbitrary functions of x , $f(x)$, $g(x)$:

$$y = f(\xi - ct) + g(\xi + ct) \quad (8)$$

If x = absolute axis, v = running velocity of the string, and the boundary condition is such that $y = 0$ when $x = 0$ and $x = L$, function f can be written

$$f(z) = f\left[\frac{2cL}{c-v} + z\right] \quad (9)$$

Namely, f is a periodic function with the period of $2cL/(c-v)$ and finally,

$$y = 2 \sum_{n=1}^{\infty} C_n \sin\left[\frac{n\pi}{cL}\{vx - (c^2 - v^2)t\} - \phi_n\right] \times \sin\frac{n\pi x}{L} \quad (10)$$

Here, n is the order of the vibration, therefore, the fundamental vibration amplitude y_1 and its frequency f_v can be written

$$y_1 = \sin\left[\frac{\pi}{cL}\{vx - (c^2 - v^2)t\} - \phi_1\right] \sin\frac{\pi x}{L} \quad (11)$$

$$f_v = \frac{|c^2 - v^2|}{2cL} \quad (12)$$

Then, the frequency f_v is expressed as follows using f_0 ,

$$f_v = f_0 \left(1 - \frac{v^2}{c^2}\right) \quad (13)$$

Fig.3. Values of the cable bending rigidity

The calculated error values, when frequency reduction during cable running is ignored, is shown in figure 4. As shown in this figure, error of this kind appears small enough-2.7 % at most- to be neglected under ordinary cable running conditions, i.e., when cable tension is more than 2.5kN, velocity less than 8 kn for armorless cables and less than 4 kn for armored cables.

4.1.3 Response

The response time of the tension measurement based on this theory depends on the travel time of the vibration along the cable. The calculated travel time, directly affecting the response time, is shown in figure.5. As shown in this figure, the response is quick enough compared with the tension varying period resulting from the pitching of the cable ships. As described above, highly accurate tension measurement is accomplished by taking cable bending rigidity and cable travel velocity into account. It is possible, however, to calculate tension within the acceptable error of 10% using only the 1st term of equation(6).

Fig.4. Error due to the cable running

Fig.5. Response time for the measurement

4.2 Outline of the tension meter

A block diagram of the tension meter is shown in figure 6, the outline of which is as follows.

(a) Vibration detection

The cable's lateral vibration frequency was detected by a noncontact, optical displacement meter suitable for systems with repeaters having bigger diameters than cables.

(b) Signal processor

The signal processor process is divided into the following 3 steps.

- (i) Deriving fundamental frequencies from the natural vibration of the cable
- (ii) Calculating the square of the frequency and then multiplying it with the specific cable coefficient, and if higher accuracy is required,
- (iii) Compensating the result of process (ii) with cable bending rigidity and velocity according to equations (6), (13)

Functions (ii) and (iii) can easily be achieved using a conventional signal processor.

The cable vibration wave form and its power spectrum detected from the non-running cable on ship board are shown in figure 7 and 8. In the experiment the cable was hit at the central part of the suspended span to activate lateral vibration of sufficient amplitude.

2nd and 3rd order vibration without bigger noise were clearly observed and are shown in figure 8. This indicates that fundamental frequencies could be derived easily through a conventional band-pass filter such as a 15 to 40 Hz, 24dB/oct band pass filter.

Fig.6. Block diagram of the system

Fig.7. Lateral vibration wave form of the cable (non-running)

Fig.8. Power spectrum of the vibration shown in Fig.7.

(c) The basic system

The relationship between cable tension and cable vibration frequency was experimentally examined on land and on shipboard.

(i) The results of the experiments on land

Experimental results are shown in figure 9. This figure shows that the calculated value coincided with an error of up to 10% when the suspended span of the cable is shorter than 2m, and 4% or less when longer than 3m. This error is considered mainly due to disregarding the bending rigidity increase occurring when cable tension increases. In other words, cable bending rigidity is expected to vary according to cable tension mainly because friction between the twisted tension members increases with cable tension. As a result, the shorter the cable span, the more the effect of disregarding the bending rigidity contributes to the error.

(ii) Test on the ship board The ship sheave was utilized as the cable suspension point for the better ship space utilization. The calculated value of the cable span which periodically varies according to the lateral vibration amplitude is shown in figure 10. As cable vibration amplitude as low as 5 to 10mm is sufficient to be detected, figure 10

indicates that only negligibly small error of within 1% is involved even with big sheave of $\phi 3000\text{mm}$.

Based on this background, the tension measuring system shown in figure 11 was set up on shipboard. A comparison of cable tension data measured directly by load cell with cable tension from vibration frequency is given in figure 12. This figure shows that the error of the new system remains a negligible 800N at most.

Fig.9. Cable tension and its vibration frequencies

Fig.10. Cable contact length on the sheave

Fig.11. Tension measuring system layout on board

Fig.12. Cable tension data from vibration detected at load cell

Fig.13. Tension measurement of non-running cable

In this case, the value of the 2nd term of equation (6) is estimated to be a negligibly small 77kN eliminating the need for compensation.

Finally, it was confirmed that the tension could be detected with a negligibly small error of less than 10% from the vibration of non-running cables when their suspended span is longer than 3m.

5. Out-at-sea tension measurement

Armorless submarine optical cable's tension was measured with the new tension meter together with ship movement and conventional tension meter data on the cable ship.

5.1 Non-running cable

The tension measuring system's lay out is shown in figure 13 with measurement results shown in figure 14. Total cable weight in water was 37kN as shown in figure 13. Measured cable tension was expected to vary around this value with the period and amplitude determined by the ship's pitching. The phase of periodically varying tension, however, was expected to be delayed by 0 to 180° from the ship's motion because of the inner friction between the cable strands and cable surface to sea water hydraulic friction.

Fig.14. On board measurements of non-running cable

As a result, the average tension values measured were 33 to 34kN by the cable vibration method and 22 kN by the conventional tension meter, both with phases 90° behind the phase of the ship's pitching.

Taking into account the cable tension absorbing effect of ship sheave rotation friction and inertia, the measured tension value by the cable vibration method is considered accurate. Here, the cable was hit occasionally to generate vibration of sufficient amplitude.

5.2 Tension measurement while cable is running

(a) Cable pay out from ship stern The power spectrum of the cable vibration while being payed out from ship stern sheave is shown in figure 15. The cable was found vibrated irregularly with sufficient amplitude caused by the water turbulence produced by the ship's propeller.

Fig.15. Power spectrum of cable vibration paid out from ship stern

(b) Cable pay out from ship bow

Naturally generated cable vibration when cable pay-out or recovery occurs from the ship bow where the sea surface is calm was found to be weak compared with that at the ship stern. Therefore, artificially generated vibration and naturally generated vibration were examined as follows.

(i) Natural vibration The tension measurement for small vibration amplitude of less than 1mm arising from shipboard vibration generated by ship thruster action or by interference from ocean waves and also by cable slipping through the cable suspending mechanism with about 100mm length platform is shown in figure 16. These effects are not sufficient enough, however, to generate good vibration under heavy tension. Therefore, from the spectrum data, cable vibration is estimated to contain its own natural frequency together with a comparable level of noise.

The power spectrum of the cable vibration thus detected demonstrating several spectrum peaks with comparable power is shown in figure 16. The resultant tension wave form derived from the natural vibration is shown in figure 17. The lack of clarity of this wave form indicates weak and noisy vibration.

Fig.16. Power spectrum of cable vibration paid out from ship bow

Fig.17. Tension data from cable vibration at ship bow

(ii) Applied vibration A 200mm roller-type cable suspending mechanism, with part of the surface cut flat in the plane perpendicular to its radial direction is shown in figure 18. The power spectrum of the vibration of the cable with one side suspended by the ship sheave and another by the roller suspender described above is shown in figure 19. The resultant tension wave form, where pulse-shaped noise per each roller revolution is observed is shown in figure 20. Cable vibration phase and the timing between the existing vibration and each new vibration generated by the roller rarely coincide, which explains why the pulse noise is generated even after processed by band pass filter. It is clear that a random vibration pattern with various frequency components is generated by the roller suspender, which triggers the specific vibration of the cable.

Using the mechanism shown in figure 18 to generate cable vibration, pay out tension of a 45km-long submarine optical cable was measured, most of the time successfully, as shown in figure 20.

Fig.18. Vibration generating roller

Fig.19. Power spectrum of the cable vibration with roller

Fig.20. Cable tension data from vibration with roller

6. Application

The tension measuring process described above can be applied to various elongated substances in general. The appropriate suspension point set-up and the vibration measuring and signal processing concept must be chosen according to the structure of the substances, required accuracy and the surrounding conditions.

In the test reported above the cable suspender pressed on the cable from below and as a result the cable was exposed to the contact pressure and was consequently bent. To avoid the problems of pressure and consequent bending, the cable can be put in between a pair of suspenders with minimum mechanical pressure. This layout minimizes adverse influences including bending stress on the cable. A suitable vibration detecting method can be chosen from among various non-contact methods including optical sensing methods and also from contact methods, for example, using an accelerometer. In addition, signal processing

procedures, in particular the method of detecting fundamental frequency from natural vibration can be improved. Instead of introducing band pass filters, the frequency with the maximum power can be subtracted from that with the 2nd highest power revealing the natural frequency of the vibration. The accuracy of the measurement can, of course, be increased by considering the bend stiffness and/or running velocity of the elongated substances. For more accurate measurement, the tension dependence of the bending rigidity of the cables will have to be taken into account.

This new method could also be used as the tension measurement methods in the manufacturing processes of the various elongated substances including optical fibers.

7. Conclusion

A new tension measuring system for submarine cables utilizing the lateral vibration frequency of cables to calculate their tension with sufficient accuracy, has been proposed. The practical performance of the method was successfully proven in an out-at-sea experiment.

The following encouraging conclusions have been obtained with the submarine optical cables.

- (1) Highly accurate measurement with an error of less than 10% can be achieved provided the cable's suspended span where the vibration is detected is longer than 3m.
- (2) A tension measuring range of up to 100kN with a response time of less than 100ms was achieved.
- (3) The new system is handy and can be temporarily installed on a small ship.

The system set-up, however, is rather complex with the vibration detecting system, signal processors and cable suspending structures. In addition, the clarity of the measured tension wave form is not always sufficient, indicating that the vibration activating method needs to be improved.

In conclusion, the new system was found to offer a safer and more accurate tension measuring method to improve the reliability of submarine cable pay-out and recovery operations.

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