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Fatigue life prediction of a cable harness in an industrial robot using dynamic simulation

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Abstract

The cable which transfers the signal and power in an industrial robot has a problem of fatigue fracture like steel components. Since the cable is very flexible compared to other components of the system, it is difficult to estimate its motion numerically. Some studies have been done on a large deformation problem, especially in a cable, and a few attempts have been made to apply the absolute nodal coordinate formulation (ANCF), which can simulate a large deformation. Only researches about the fatigue life of structural cables or comparative studies of FEM and ANCF simulations can be found. This paper presents a method to simulate the behavior of the cable harness using the ANCF and to predict the fatigue life while computing the strain time history of the point of interest. Rigid body dynamics is applied for the robot system, while ANCF is used for the cable harness. The simulation is performed by using the dynamic analysis process. The material property of the cable is obtained by a test. A simplified model is prepared. With these data, the behavior of the cable is simulated and the fatigue life is predicted.

Keywords: Absolute nodal coordinate; Dynamic analysis; Fatigue life prediction; Cable harness

1. Introduction

Mechanical systems such as robots, automotive and railway vehicles are constantly required to be faster and lighter than before. Naturally, concern for the deformation of the components has been growing, but ignored because it was not a big problem previously. That is, the current trend in design may easily lead to a structural failure fatigue fracture. The concern of this paper is focused on how to predict the fatigue life of the cable harness in an industrial robot. A cable harness in a robot system performs multi-purpose tasks such as transmitting signal information, electric power, and even transferring hydraulic liquid simultaneously. A cable harness is composed of several materials such as plastic, insulation and conductors, so that the conventional fatigue life prediction method is not directly applicable to the cable. There are some difficulties. First, traditional experiments in the actual field or accelerated testing in the research laboratory have been used to estimate the fatigue life of a component, but both require much time and cost. Second, actual testing hardware must be provided. Third, even if such hardware is available, the processes include attaching a strain gage on the cable and gathering reliable test data. Due to the difficulties mentioned above, the fatigue life of a cable relies on standard test results which are based on ideal test environments or ad hoc experience, without any specific estimation of the fatigue life of the cable. However, these difficulties can be avoided by using the proposed computational simulation [1-3]. To utilize the model, three steps are needed. First, properties of the material and its S-N curve should be obtained. Those are created by the recursive test by the manufacturer. Second,

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dynamic stress time history or strain time history should be created during the simulation. Time history is created on the interest point during the movement of the robot. There are two approaches to find the time history on the interest point: data accumulation from the experiment and from the simulation. The absolute nodal coordinate formulation (ANCF) is adopted to simulate the model. Third, the cycle counting method using the law of linear damage accumulation, damage summation method and prediction of the life are needed. In this paper, these procedures are used to present a method to predict fatigue life of a cable harness in an industrial robot.

2. Equations of motion using ANCF

Recently, Shabana [1] presented a method which can solve nonlinear large displacement of a very flexible body using the absolute nodal coordinate system, which is derived by introducing continuum mechanics theory and finite element method [4, 5]. In this paper, ANCF is used to derive the equations of motion for the cable harness system.

2.1 Displacement representation in absolute nodal coordinate formulation (ANCF)

Fig. 1 shows a position vector on the beam element *e*. Several beam elements can be used to represent a very flexible elastic body *e* [6-8].

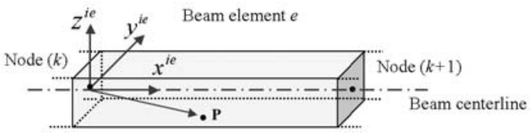

Fig. 1. Local element coordinates of a beam element.

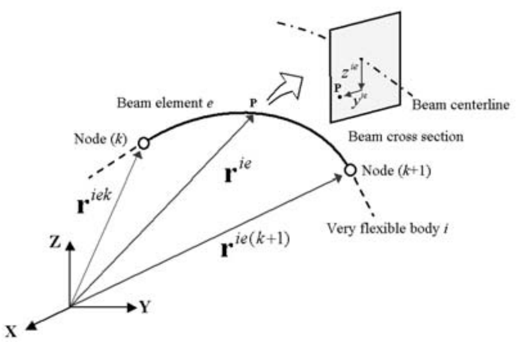

Fig. 2. Deformation of a beam element in the absolute nodal coordinate formulation.

A beam element has two nodes as in Fig. 1. Fig. 2 shows each node can be expressed with global position vector and slope in absolute nodal coordinates as in Eq. (1).

$$\mathbf{e}^{ie} = \left[\mathbf{e}^{ie_k T}, \mathbf{e}^{ie_{k+1} T}\right], \qquad \mathbf{e}^{ie_k} = \left[\mathbf{r}^{ie_k T}, \left(\frac{\partial \mathbf{r}^{ie_k}}{\partial x^{ie}}\right)^T, \left(\frac{\partial \mathbf{r}^{ie_k}}{\partial y^{ie}}\right)^T, \left(\frac{\partial \mathbf{r}^{ie_k}}{\partial z^{ie}}\right)^T\right] \tag{1}$$

$\mathbf{r}^{ie_k}$ denotes a global position vector which is the location of the node k and $\partial \mathbf{r}^{ie_k}/\partial x^{ie}$, $\partial \mathbf{r}^{ie_k}/\partial y^{ie}$ and $\partial \mathbf{r}^{ie_k}/\partial z^{ie}$ are gradients of the global position vector. Since the beam is treated as a three-dimensional solid, the rotary inertia effect and torsion can be considered. The arbitrary global position vector of a point in a beam can be written as Eq. (2) by using the shape function, $\mathbf{S}^{ie}$ and absolute nodal coordinate, $\mathbf{e}^{ie}$ in Eq. (1).

$$\mathbf{r}^{ie} = \mathbf{S}^{ie}(x^{ie}, y^{ie}, z^{ie})\mathbf{e}^{ie}(t) \tag{2}$$

2.2 Mass matrix and elastic force

Kinetic energy of a three-dimensional beam element *e* can be written as Eq. (3) by using the continuum mechanics theory of the beam [1, 4, 5].

$$T^{ie} = \frac{1}{2}\int_{V^{ie}} \rho^{ie} \dot{\mathbf{r}}^{ie^T} \dot{\mathbf{r}}^{ie} dV^{ie} = \frac{1}{2}\dot{\mathbf{e}}^{ie^T}\left(\int_{V^{ie}} \rho^{ie}\mathbf{S}^{ie^T}\mathbf{S}^{ie} dV^{ie}\right)\dot{\mathbf{e}}^{ie} = \frac{1}{2}\dot{\mathbf{e}}^{ie^T} M^{ie}\dot{\mathbf{e}}^{ie} \tag{3}$$

Here, ρ^{ie} and V^{ie} denote density and volume and M^{ie} is a mass matrix. Elastic potential energy of the beam element *e* can be written as Eq. (4).

$$U^{ie} = \frac{1}{2}\int_{V^{ie}} \varepsilon^{ie^T} E^{ie} \varepsilon^{ie} dV^{ie} = \frac{1}{2}\mathbf{e}^{ie^T} K_a^{ie}\mathbf{e}^{ie} \tag{4}$$

Here, K_a^{ie} is a stiffness matrix of the three-dimensional beam element *e* which is expressed by using nonlinear functions from the absolute nodal coordinates. The elastic force vector can be obtained by differentiating the elastic potential energy with generalized coordinates as in Eq. (5).

$$\mathbf{Q}_k^{ie} = -\left(\frac{\partial U^{ie}}{\partial \mathbf{e}^{ie}}\right) \tag{5}$$

2.3 Strain and dynamic stress

The elastic force of a three-dimensional beam can be calculated by continuum mechanics theory. In this case, the relationship between strain and displacement relationship is the key to generating the general elastic force formulation. The stress is calculated by using strain. Using the Cauchy-Green equation, Lagrangian strain tensor ε_m^{ie} is defined as in Eq. (6).

$$\varepsilon_m^{ie} = \frac{1}{2}\left(\mathbf{D}^{ie\,T}\mathbf{D}^{ie} - \mathbf{I}\right) = \begin{bmatrix} \varepsilon_{11}^{ie} & \varepsilon_{12}^{ie} & \varepsilon_{13}^{ie} \\ \varepsilon_{21}^{ie} & \varepsilon_{22}^{ie} & \varepsilon_{23}^{ie} \\ \varepsilon_{31}^{ie} & \varepsilon_{32}^{ie} & \varepsilon_{33}^{ie} \end{bmatrix}$$
$$= \frac{1}{2}\begin{bmatrix} \mathbf{r}_{,X}^{ie\,T}\mathbf{r}_{,X}^{ie} - 1 & \mathbf{r}_{,X}^{ie\,T}\mathbf{r}_{,Y}^{ie} & \mathbf{r}_{,X}^{ie\,T}\mathbf{r}_{,Z}^{ie} \\ & \mathbf{r}_{,Y}^{ie\,T}\mathbf{r}_{,Y}^{ie} - 1 & \mathbf{r}_{,Y}^{ie\,T}\mathbf{r}_{,Z}^{ie} \\ symmetric & & \mathbf{r}_{,Z}^{ie\,T}\mathbf{r}_{,Z}^{ie} - 1 \end{bmatrix} \qquad (6)$$

Here, I is the 3×3 identity matrix and $\mathbf{r}_{,\alpha}^{ie} = \partial\mathbf{r}^{ie}/\partial\alpha$, $\alpha = X,Y,Z$. Time response of the strain calculated in Eq. (6) can be used as dynamic strain time history (DSTH). This indicates that DSTH can be obtained from the dynamic simulation by using Eq. (7).

$$\boldsymbol{\sigma}^{ie} = \mathbf{E}^{ie}\ \boldsymbol{\varepsilon}^{ie} \qquad (7)$$

Here, matrix $\mathbf{E}^{ie}$ is the elastic coefficient matrix of the beam material. The elastic coefficient matrix $\mathbf{E}^{ie}$ for an isotropic homogeneous material is defined as follows, using the constants λ and μ .

$$\mathbf{E}^{ie} = \begin{bmatrix} \lambda+2\mu & \lambda & \lambda & 0 & 0 & 0 \\ \lambda & \lambda+2\mu & \lambda & 0 & 0 & 0 \\ \lambda & \lambda & \lambda+2\mu & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu \end{bmatrix} \qquad (8)$$

Here, $\lambda = \frac{E\upsilon}{(1+\upsilon)(1-2\upsilon)}$, $\mu = \frac{E}{2(1+\upsilon)}$. E is Young's modulus of elasticity and υ is the Poisson ratio.

3. Derivation of a bracket joint

The motion of the rigid and flexible body is governed by the interconnected joint. To model this joint properly, a mixed generalized coordinate system is implemented. The 3-dimensional joint constraint equations using a mixed coordinate system have been developed in this paper [6]. A bracket joint eliminates 6 degrees of freedom from the system. Using a bracket joint, the dynamic model of combined rigid and flexible bodies can be defined easily since joints and force elements defined for rigid bodies can be used by connecting a dummy body in between the rigid body and flexible body with a bracket joint. Constraint between two flexible bodies can be realized by defining a dummy body. Constraint equations for a bracket joint can be defined as in Eq. (9). q^i and q^j represent the generalized coordinates of bodies i and j. $\mathbf{v}_i, i = 1,\ 2,\ 3$ represents the unit vector along joint coordinate system, i, j and k in Fig. 3.

$$\Phi^{cs}\left(q^i, q^j\right) = \begin{bmatrix} \Phi^s \\ \Phi^{d-1} \\ \Phi^{d-2} \\ \Phi^{d-3} \end{bmatrix} = \begin{bmatrix} \mathbf{r}_p^j - \mathbf{r}_p^i \\ \mathbf{v}_1^{i^T}\mathbf{v}_2^j \\ \mathbf{v}_1^{i^T}\mathbf{v}_3^j \\ \mathbf{v}_2^{i^T}\mathbf{v}_1^j \end{bmatrix} = 0 \qquad (9)$$

Other constraints can also be constructed by a similar procedure. One spherical joint and three dot product constraints are used [7].

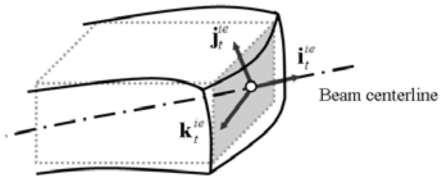

Fig. 3. Definition of the tangential frame for the joint.

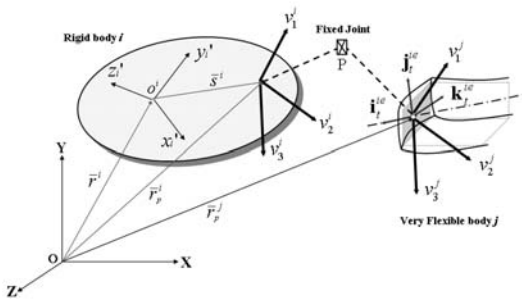

Fig. 4. Graphical illustration of a bracket joint.

To define the joint, the tangent frame [6] at the node for joints must be defined as in Fig. 3. And, using Eq. (9), constraint equations can be derived by using the vectors in Fig. 4. The velocity and acceleration equations can be obtained by time differentiation of the constraint equations. Once the velocity and acceleration equations are derived, these can be applied to the equations of motion which will follow.

4. Equations of motion

The equations of motion of a large deformable body by using ANCF are assembled using the general matrix assembly method, such as direct stiffness method and QR matrix decomposition. This method is closely related to FEM [2, 9]. Equation (10) shows the equations of motion of an elastic body.

$$\mathrm{M}^i\ddot{\mathbf{e}}^i + \Phi_e^T\boldsymbol{\lambda} = \mathrm{Q}_e^i + \mathrm{Q}_k^i + \mathrm{Q}_d^i \tag{10}$$

Here, M^{i} is mass matrix of the elastic body i. $\mathrm{Q}_{\mathrm{k}}^{\mathrm{i}}$ is the elastic force vector, $\mathrm{Q}_{\mathrm{e}}^{\mathrm{i}}$ is the general force vector due to gravity and spring-damper system. And $\mathrm{Q}_{\mathrm{d}}^{\mathrm{i}}$ is the damping vector derived from the structural damping characteristic of an elastic body i. The Lagrange multiplier, λ, is used to include the constraint Jacobian matrix from the constraint equation, Φ_e. Equation (11) is the second derivative of the constraint equation, Φ_e, for acceleration analysis.

$$\Phi_e\ddot{\mathbf{e}}^i = -(\Phi_e\dot{\mathbf{e}}^i)_e\dot{\mathbf{e}}^i - 2\Phi_{e\,t}\dot{\mathbf{e}}^i - \Phi_{tt} = \boldsymbol{\gamma} \tag{11}$$

Combining Eqs. (10) and (11), mixed equations of motion of a multibody system with rigid bodies and very flexible bodies can be written as Eq. (12).

$$\begin{bmatrix} \mathrm{M}_r & 0 & \Phi_{q_r}^T \\ 0 & \mathrm{M}_e & \Phi_e^T \\ \Phi_{q_r} & \Phi_e & 0 \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_{\mathbf{r}} \\ \ddot{\mathbf{e}} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathrm{Q}_{\mathbf{r}} \\ \mathrm{Q}_{\mathbf{e}}^{\mathrm{Total}} \\ \boldsymbol{\gamma} \end{bmatrix} \tag{12}$$

Here, M_e is the mass matrix of ANCF system and $\mathrm{Q}_{\mathbf{e}}^{\mathrm{Total}} = \mathrm{Q}_e + \mathrm{Q}_k + \mathrm{Q}_d$. The subscript letters r and e indicate the rigid body system and ANCF system, respectively.

5. Simulation and fatigue life prediction

The fatigue life of a cable harness is calculated by using the dynamic stress in Eq. (7) with the strain from the elastic force calculation in Eq. (5). The procedure is summarized in Fig. 5.

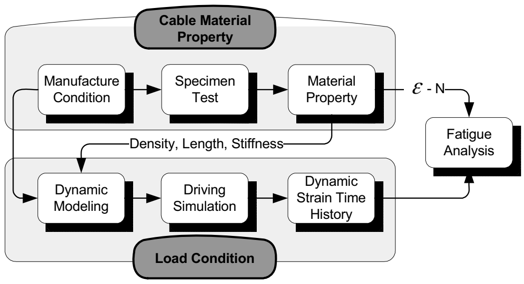

Fig. 5. Main procedure.

Fig. 6. The example of cable harness.

Similar to the cable harness example in Fig. 6, the cable is composed of various materials, such as insulate, plastic, and copper. Therefore, it is very difficult to denote one value for the overall material properties of a cable harness, although material properties of each component are available in reference [10].

For this reason, the cable is simplified as a homogeneous material. The cable harness tensile test to obtain the material property of the cable is not affordable because of its adversity to test environment. In this study, the cable is modeled as a very flexible beam. The best assumed composite stiffness can be found by trial and error in the process of comparison between the displacement from the simulation and high-speed camera test of the one-side clamped cable as in Fig. 7.

Dynamic strain time history, ε^{ie} in Eq. (6), is extracted from the dynamic simulation and dynamic stress σ^{ie} in Eq. (7) is calculated simultaneously. Computed dynamic stress tensor can be converted into principal stress. Fatigue life is estimated with the commercial fatigue analysis program, FE-fatigue, with the data collected previously, principal stress and S-N curve. From the reference [3], 3 beam elements

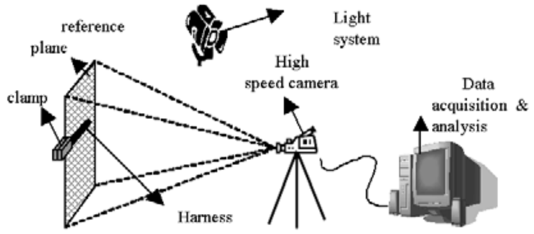

Fig. 7. The test of one-side clamped cable.

Table 2. Material properties of robot arm model.

Name	Data	
Base	Ground Fix	Rigid
Assumed Cable Harness	Total Length: 0.3 *m* Width : 0.02 *m* Height : 0.02 *m* Density : 4200 kg/m^3 E : 400,000,000 N/m^2 G : 200,000,000 N/m^2	3 Beam Elements (4 nodes)
Robot Arm	Mass (*kg*): 10.0 I_{xx}, I_{yy}, I_{zz} (kg/m^3): 0.1	Rigid

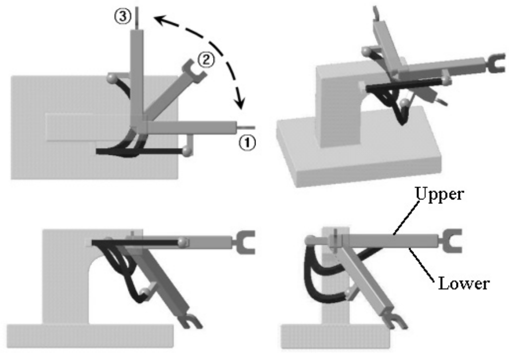

Fig. 8. Simulation of the model.

are thought to be enough to simulate the behavior of the cable.

Assumed material properties from the test in Fig. 7 are used and the S-N curve of the cable harness is referenced from ref. [11]. In ref. [11], there are numerous experiments and assorted dataset for fatigue analysis. The material properties of the model used for analysis are summarized in Table 2. As shown in Fig. 8, the driving constraint is imposed on the robot arm to operate according to the sequence of '①→②→③→②→①' The sequence comes from the actual movement in the work place. As seen in Fig. 9, maximum principal stress occurs on the upper interest point of the first element (Elem1_top) in wire harness

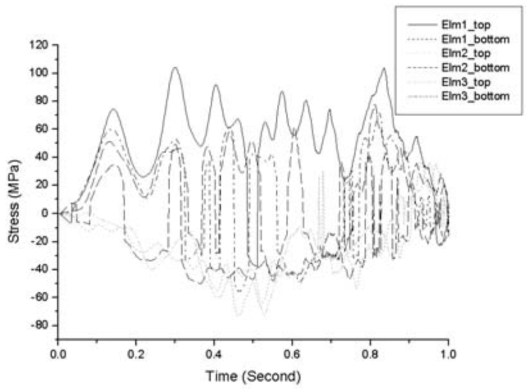

Fig. 9. Maximum principal stress time history of elements.

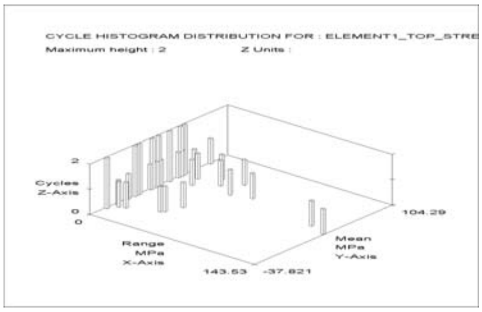

Fig. 10. Cycle counting of principal stress of Elem1_top.

Table 3. Life prediction of the robot cable harness component.

Mean Stress Method	Goodman	Gerber	No Mean
Ⓐ Elem. 1 – Top	1.99E+5	6.07E+5	7.46E+5
Ⓑ Elem. 1 – Bottom	9.95E+6	1.15E+7	1.15E+7
Ⓒ Elem. 2 – Top	9.62E+6	5.84E+6	5.57E+6
Ⓓ Elem. 2 – Bottom	1.21E+6	1.63E+6	1.66E+6
Ⓔ Elem. 3 – Top	8.67E+6	5.46E+6	5.25E+6
Ⓕ Elem. 3 – Bottom	1.29E+6	2.17E+6	2.25E+6

of Table 2. The first element is a directly fixed element with the base.

Fig. 10 shows the cumulative number of the rainflow cycle on the upper side of the first element by extracting fatigue cycles according to a rainflow algorithm. Table 3 contains the meaningful synthetic results from the cable harness deformation simulation. As shown in Table 3, the top of the element 1 has the shortest fatigue life. If the target life can be defined, this result will be meaningful when a product is developed.

6. Conclusion

Equations of motion of a combined system to simulate the cable harness in the robot are presented based on the theory of the absolute nodal coordinate formulation and FEM analysis methods using the shape function. With the proposed research, a numerical model for the combined system is derived. Dynamic strain and stress of the large deformable beam can be calculated at the same time during multibody dynamic analysis with this formulation. Furthermore, structural characteristics of an elastic body, not to mention the dynamic characteristics, can be easily obtained. A bracket joint is derived that interconnects between a rigid and a very flexible body. The proposed method is applicable to the cable harness of the robot to study its behavior. Moreover, these studies can be extended to study the prediction of fatigue life in addition to the study of cable harness behavior. In summary, the fatigue life prediction procedure for a cable harness is developed, previously designed by a user's experience and an arbitrary development procedure. Furthermore, the fatigue life prediction procedure presented in this study will be useful for a system with very flexible bodies like the catenary system of KTX.

References

[1] A. A. Shabana, Computer implementation of the absolute nodal coordinate formulation for flexible multibody dynamics, *Journal of Nonlinear Dynamics* 16 (1998) 293-306

[2] J. H. Seo, Dynamic analysis method and its applications for very flexible multibody systems, Dissertation, Ajou University, (2005)

[3] A. A. Shabana and R. Y. Yakoub, Three dimensional absolute nodal coordinate formulation for beam elements: theory, *Transaction of the ASME* 123 (2001) 606-613

[4] A. A. Shabana, Flexible multibody dynamics: review of past and recent developments, *Journal of Multibody System Dynamics* 1 (1997) 189-222

[5] D. Vallejo, J. Mayo, J. L. Escalona and J. Dominguez, Efficient evaluation of the elastic forces and jacobian in the absolute nodal coordinate formulation, *Journal of Nonlinear Dynamics* Vol. 35 (2004) 313-329

[6] A. A. Shabana, Dynamics of Multibody Systems, 2nd Edition, Cambridge University Press, Cambridge, USA, (1998)

[7] E. J. Haug, Computer-Aided Kinematics and Dynamics of Mechanical Systems, Vol. I : Basic Methods, Allyn and Bacon, USA, (1989)

[8] W. S. Yoo, S. J. Lee and J. H. Sohn, Large oscillations of a thin cantilever beam: physical experiments and simulation using absolute nodal coordinate formulation, *Journal of Nonlinear Dynamics* 34 (2003) 3-29

[9] Bathe, K. J., Finite Element Procedures, Prentice-Hall, USA, (1995)

[10] J. A. Bannantine, J. J. Comer and J. L. Handrock, Fundamentals of Metal Fatigue Analysis, Prentice Hall, USA, (1990)

[11] Product Catalog, Hitachi Cable Co.