博士論文（要約）

Damage Identification of Belt Conveyor Support Structure Based on Cross-sectional Vibration Modes

(断面振動モードに基づいたベルトコンベア支持構造物の損傷同定)

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Belt conveyors, widely used in various industries worldwide, are often exposed to corrosive environment. In case of ironworks, dust falls from the belt and adhere firmly to the support structure. Accumulated dust together with moisture provides a severe corrosive environment. Decades after construction, many of these support structures have severe degradation, which may cause structural failure and functional stop of associated industries. Furthermore, there is risk of the loss of human lives due to structural failures. Belt conveyors need appropriate maintenance based on the assessment of their structural condition.

The damage identification of these structures is, however, difficult due to several reasons such as the possible presence of several corroded members in a single support structure, non-structural members which are sometimes updated, large amounts of dust accumulated and firmly attached on structural members, and the unavailability of initial condition of the structure. While the use of specific local vibration modes has been proposed to identify damages on secondary members of the support structures even under these difficulties, this method is not applicable to the longitudinal main member of the structure, which is continuous and much stiffer than the secondary member; the method cannot deal with the dust accumulation theoretically, either.

This thesis addresses the damage identification problem of the belt conveyor support structure utilizing cross-sectional vibration characteristics. Numerical study is first performed by FE Modelling to clarify cross-sectional vibration characteristics through sensitivity and observability analysis. Then experimental validation follows.

The eigenvalue analysis of the support structure reveals that there exist some modes in which only the longitudinal main member vibrates strongly as compared to other parts of the structure in the cross-sectional direction of the member. These vibration modes are defined as cross-sectional modes (CSM) of the main members. In the cross sectional modes, both web and flange of the main member vibrate in phase in the out-of-plane direction. In addition, there exist a nodal line along the longitudinal direction of the member where vibration amplitude is much smaller than the free edges.

When a part of the continuous member is damaged, the cross-sectional mode becomes localized to the damaged panel; a panel is a unit portion of the support structure in the longitudinal direction constrained by two neighboring secondary members. The modal amplitudes of the rest of the main members remain small. In addition, the local vibration frequency decreases significantly from CSM; the frequency change is sensitive to damage. This mode is named as the localized cross-sectional mode (LCSM). On the other hand, the damaged member does not vibrate at the CSM frequencies. Furthermore, the presence of damage on a panel affects CSM frequencies and LCSM frequencies of other panels marginally. Hence the cross-sectional modes are good damage features of the main member even when multiple damages exist on a structure. The damaged panel is identified through the frequency comparison of the LCSM and CSM.

Accumulation of dust, which is common at ironworks, also changes the vibration properties of CSM and LCSM. When a damaged member has dust accumulation, both the stiffness loss and mass increase affect the vibration characteristics; the effects of these two need to be separated for the damage identification. To overcome this problem, the dynamically measured flexibility matrix, or modal flexibility matrix, is evaluated. It has been proved numerically and theoretically that dynamically measured flexibility matrix is independent of mass change whereas the matrix is dependent on the stiffness change. By utilizing LCSM frequencies and mode shapes, a local modal flexibility is determined. This local modal flexibility determined based on cross-sectional vibration modes is termed as cross-sectional mode based local flexibility matrix, CSMLF matrix. When there is change in stiffness of the damaged panel, this local flexibility matrix will change. On the other hand, when there is mass change, the matrix remains unchanged. The damaged panel is identified by estimating the CSMLF matrix even with dust accumulation.

Then, thickness evaluation of identified damaged member is investigated. Due to the limited measurement points and accuracy in practice and spatially-distributed non-uniform corrosion, the thickness evaluation is an ill-posed problem. However, with some assumptions, thickness is approximately evaluated. The assumptions are that the damaged region in the panel are identifiable and that thickness are uniform over the damaged region resulting in a single damage variable to be identified. The method is examined by locating the probable damaged region first and determining the thickness of the identified region by updating the analytical model to minimize the difference between the CSMLF matrix of the analytical model and the matrix experimentally identified. Numerical simulations indicate that the thickness of the damaged member is identified under the assumptions.

To determine modal flexibility matrix from vibration measurement without the need of mass matrix information of the target member, a system identification technique is utilized. Modal analysis and state space realization based on the eigensystem realization algorithm (ERA) are performed on input-output vibration data to obtain the CSMLF matrix.

The damage identification method is validated through experiments on a decommissioned support structure utilizing non-contact measurement using Laser Doppler Vibrometer. CSM and LCSM of the main member are observed and corroded members are identified by comparing the frequencies. Then, the CSMLF matrix is constructed from densely measured data based on state space realization. The damage is simulated by grinding a part of main members to reduce the cross section area. Mass change is simulated by attaching magnet pieces. Independence of the CSMLF matrix with respect to mass change is confirmed. On the other hand, the CSMLF matrices of the damaged and undamaged members are shown to have large differences. Using the CSMLF matrix, even a damaged panel with added mass is identified as the damaged panel with stiffness reduction. The proposed method is thus experimentally shown to possess the capability to evaluate stiffness reduction of the support structure even under changes in mass.