# Digital Twin for Diagnosis of Belt Looseness in HVAC Systems using multi-body dynamics simulation

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## ABSTRACT

Most heating, ventilation, and air conditioning (HVAC) systems operate using a belt pulley system that provides high efficiency at a low cost. To monitor the health of the HVAC system, it is essential to detect looseness, which is one of the primary failure modes of belt-pulley systems. The main feature used to identify looseness is belt slip, which can be computed using the ratio of angular velocity and diameter between the drive pulley and driven pulley. However, accurately diagnosing the condition of the HVAC system based on the slip distribution calculated by measuring the rotational speed can be based on empirical criteria. To overcome this problem, this paper proposes constructing a digital twin model for accurate diagnosis of belt loosening in HVAC systems. The proposed approach involves performing multi-body dynamics (MBD) based time-domain analysis considering uncertainty. To validate the proposed model, belt looseness is applied to the HVAC system, and the slip distribution is calculated and compared with the results computed by the digital twin model. Through this comparison, it was demonstrated that the proposed model can be utilized to diagnose belt looseness in the HVAC system.

## 1. INTRODUCTION

Belt-pulley systems are widely used in various industrial applications, such as compressors, pumps, and fans, due to their high efficiency, tolerance for misalignment, and low cost. However, over time, these systems may lose their mechanical properties, leading to failure modes such as belt rupture, severe pulley wear, or excessive belt slip. Among these failure modes, belt looseness is a significant issue as it increases the belt slip, accelerating the wear process of the transmission system.



This paper proposes a digital twin (DT) developed to diagnose belt loosening in a typical HVAC system that employs a belt-pulley system. Since the HVAC system is composed of several parts, multi-body dynamics (MBD)-based simulation accurately models the interaction force and motion between parts. Additionally, the accuracy of the DT model is verified by conducting experiments on the HVAC system's test bed and comparing the results with simulations.

This paper is organized as follows: Section 2 provides an overview of digital twin technology and belt looseness. Section 3 describes the proposed MBD-based digital twin. Section 4 presents a case study of the HVAC system with belt looseness. Finally, Section 5 concludes the paper and discusses future work.

## 2. A BRIEF OVERVIEW OF DIGITAL TWIN AND BELT LOOSENESS

### 2.1. Digital Twin

A digital twin (DT) is an advanced cyber-physical system that facilitates real-time monitoring, analysis, and control of physical systems by creating a virtual model that precisely replicates the behavior and properties of the physical system. This virtual model allows for simulation, prediction, and optimization of performance and can be used to enhance the system's efficiency, reliability, and sustainability. (Grieves, 2017).

A high-fidelity model is required from a simulation perspective to create the DT that accurately represents the state of the system. However, numerical simulations of these high-fidelity models are often expensive and inefficient, making engineering and control design studies difficult and sometimes impossible (Hartmann et al., 2018). Recently, one possible approach to address this problem is the use of reduced-order models (ROMs), which aim to construct less complex surrogate models while replicating the essential dynamics of high-fidelity systems (Lee et al., 2023).

### 2.2. Belt Looseness

In mechanical systems that incorporate belts, appropriate tensioning is critical to prevent belt looseness. If the tension is too low, the belt may slip or become loose, while excessive tension may cause premature wear and damage, resulting in stretched or loose belts in a short period. Additionally, misalignment between the belt and pulleys or other components in the system can cause the belt to become loose and lead to operational issues.

The belt slip is defined as the amount of sliding that occurs between the belt and the pulley, expressed as a percentage of the belt's linear speed as follows:

$$s_{\Omega} = 100 \times \left(1 - R_t \frac{\Omega_{load}}{\Omega_{motor}}\right) \quad (1)$$

where $\Omega_{motor}$ and $\Omega_{load}$ are the motor and load mechanical speed, respectively; $R_t$ is the transmission ratio. The reason for using slip is to quantify the amount of force lost due to slipping of the belt on the pulley. When the belt slips, it loses contact with the pulley, reducing friction and the amount of power transferred from the drive pulley to the driven pulley. This slippage affects the performance of the system by reducing the rotational speed of the driven pulley. A study to evaluate belt slack by measuring and analyzing slip was conducted (Antoine et al, 2017).

## 3. PROPOSED MULTI-BODY DYNAMICS (MBD)-BASED DIGITAL TWIN

This section introduces the proposed multi-body dynamics (MBD)-based digital twin for detecting belt looseness. The model utilizes RPM data to detect belt looseness and calculates the slip through signal processing. The slip is determined through MBD modeling and simulation, and compared with experimental results.

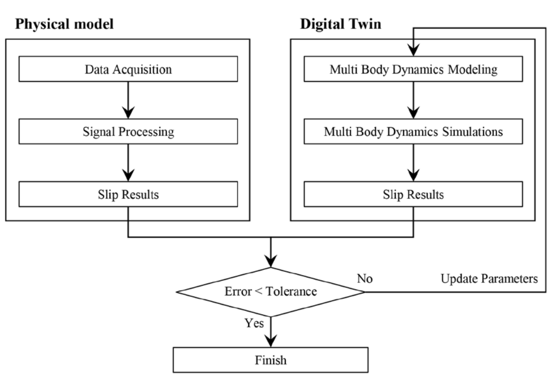


Figure 1. Flow chart of the proposed digital twin

The MBD based-digital twin is created by updating the model with parameter modifications until the error is less than the criterion tolerance. Figure 1 depicts the flowchart of the proposed method.

### 3.1. Multi-Body Dynamics

Multi-body dynamics (MBD) is an area of study that focuses on analyzing the motion of interconnected bodies subject to forces acting on the bodies. The dynamic analysis yields information on the interaction forces between the bodies as well as the resulting motion of the bodies. Classical MBD is concerned with rigid body dynamics, where the analysis results in the determination of reaction forces or frictional forces at specified constraint locations, such as position, velocity, acceleration, and joint conditions for each body, along with external forces applied to the system and contact forces when contact occurs. By performing MBD, it is possible to calculate and design the dynamic behavior of the system and the loads applied to each component.

To perform accurate analyses that consider the effects of deformation, a combination of MBD and finite element method (FEM) is used. FEM is a numerical method that analyzes the stress and deformation of flexible bodies. Combining MBD with FEM allows for the analysis of systems that include both rigid and flexible bodies.

### 3.2. Modeling of Flexible Body

FEM is widely used for modeling flexible bodies in structural dynamics. Beam and shells in the classical FEM are considered as non-isoparametric elements. The use of displacements and infinitesimal rotations in the local element frame as nodal coordinates leads to linearized equation of motion, which cannot describe exactly the rigid body motions.

To overcome this problem, several methods are developed for the kinematic description of the motion of the flexible bodies with large displacements. One of the representative methods is the absolute nodal coordinate formulation (ANCF). In this method, beams and shells can be considered as isoparametric elements by using the nodal displacements and slopes in the global coordinate as the nodal coordinates to obtain exact the rigid body motions. However, in a thin and stiff structure, the ANCF coupled deformation modes has a very large high frequency, resulting in very small-time steps in the time integration, which reduces the computational efficiency.

Another technique for solving problems with large displacements is the finite segment method (FSM). FSM assumes that a flexible body consists of a set of rigid bodies connected by springs and dampers. This method is relatively simple because the elasticity determined by the stiffness of the spring can be defined by the element theory used in FEM.

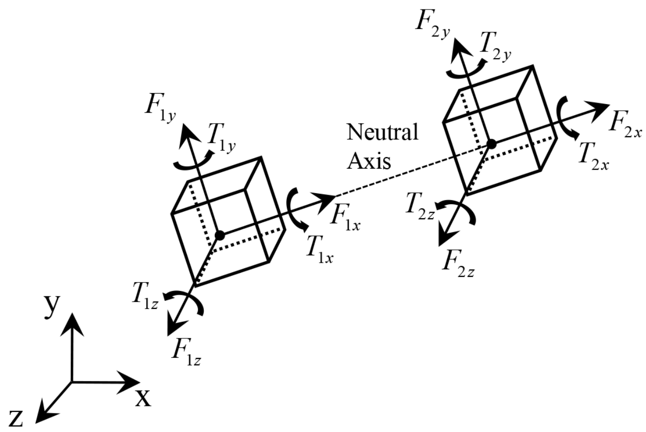


Figure 2. The kinematic description of finite segment method (FSM)

As shown in Figure 2, the concept of FSM (which is called beam-force in RecurDyn) is that all segments are defined as rigid bodies, and the flexibility between each segment is modeled as a spring connection. Each rigid body segment has 6 DOFs and consists of 3 independent Cartesian coordinates and 3 Euler angles. The mass matrix $\mathbf{M}^i$ in the i-th element is defined as follows:

$$\mathbf{M}^i = \begin{bmatrix} \bar{\mathbf{M}}_1 & & & \\ & \bar{\mathbf{I}}_1 & & \\ & & \bar{\mathbf{M}}_2 & \\ & & & \bar{\mathbf{I}}_2 \end{bmatrix} \tag{2}$$

where $\left(\bar{\mathbf{M}}, \bar{\mathbf{I}}\right) \in \mathbb{R}^{3\times3}$ denote the lumped mass matrix and inertia tensor of the rigid body. The forces and torque in the i-th element are defined as follows:

$$\mathbf{F}^i = \begin{bmatrix} \mathbf{F}_1 \\ \mathbf{T}_1 \\ \mathbf{F}_2 \\ \mathbf{T}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{F}_1 \\ \mathbf{T}_1 \\ -\mathbf{F}_1 \\ -\mathbf{T}_1 - d_{12} \times \mathbf{F}_1 \end{bmatrix} \tag{3}$$

where $d_{12}$ is an instantaneous vector from the rigid body 1 to the rigid body 2; $\{\mathbf{F}_1, \mathbf{F}_2\}$ and $\{\mathbf{T}_1, \mathbf{T}_2\}$ are forces and torques acting on the rigid body, respectively. The forces and torque are defined by Timoshenko beam theory. (Hutchinson, J. R, 2001)

### 3.3. Contact and Friction Model

A belt-pulley system is a mechanism that utilizes a rubber belt to transmit power to a destination that requires two or more rotations. It is essential to accurately analyze the contact interface between the belt and the pulley to ensure efficient operation. To construct a robust analysis model, it is necessary to determine the contact point accurately and calculate the contact and friction forces.

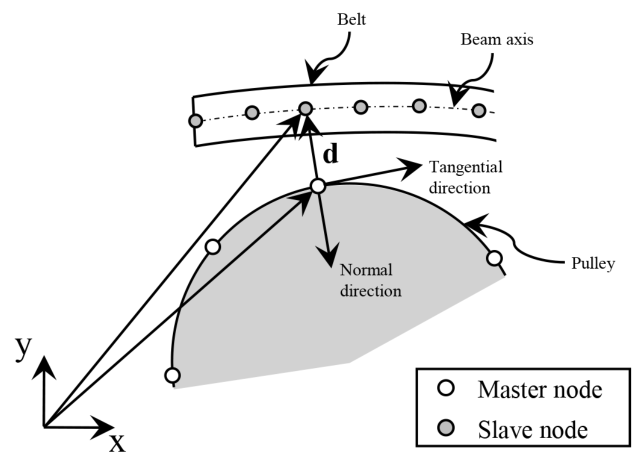


Figure 3. The description of belt-pulley contact

As shown in Figure 3, a series of contact meshes are created for the interface where the belt and pulley contact. Each set of contact meshes can be defined as masters and slaves. In a pair of contact elements comprising a master set and a slave set, the contact force acting at the point where the contact is detected can be expressed as follows (Hunt, 1975):

$$F_n = K\delta^n\left(1 + D\dot{\delta}\right) \tag{4}$$

where $K$ , $D$ are the contact stiffness and damping, respectively; $\delta$ is penetration depth, $\dot{\delta}$ is relative velocity of penetration depth, and $n$ is Hertz contact exponent. The penetration can be calculated from the vector $\mathbf{d}$. The friction force is modelled using Coulomb friction as follows (Mostaghel, 1975):

$$F_f = -\mu F_n \tanh\left(\frac{v_t}{v_{th}}\right) \tag{5}$$

where $\mu$ is friction coefficient, $v_t$ is tangential velocity, and $v_{th}$ is the threshold of velocity.

### 3.4. Kinematic Constraints and Global equation of motions

Kinematic constraints are often utilized to establish connections between components in a numerical model. One of the major benefits of kinematic constraints is that they help to maintain the stability of time integration, despite the potential increase in the overall size of the equation of motion. The general kinematic constraint equation is typically expressed as:

$$\mathbf{\Phi}(t,\mathbf{x}) = \mathbf{0} \tag{6}$$

where $\mathbf{x}$ is the vector including the position and Euler-angle of rigid body. The derivative of Eq. (6) with respect to time can be written as follows:

$$\dot{\mathbf{\Phi}} = \mathbf{\Phi}_{\mathbf{x}}\dot{\mathbf{x}} + \mathbf{\Phi}_{\mathbf{t}} = \mathbf{0} \tag{7}$$

Also, differentiating Eq. (7) with respect to time yields

$$\begin{aligned}\ddot{\mathbf{\Phi}} &= \mathbf{\Phi}_{\mathbf{x}}\ddot{\mathbf{x}} + \left(\mathbf{\Phi}_{\mathbf{x}}\dot{\mathbf{x}}\right)_{\mathbf{x}}\dot{\mathbf{x}} + \mathbf{2}\mathbf{\Phi}_{\mathbf{xt}}\dot{\mathbf{x}} + \mathbf{\Phi}_{\mathbf{tt}} \\ &= \mathbf{\Phi}_{\mathbf{x}}\ddot{\mathbf{x}} + \boldsymbol{\gamma} = \mathbf{0}\end{aligned} \tag{8}$$

The constraint equations with respect to various joint conditions can be deduced based on Eq. (6) to Eq. (8).

The global equations of motion with $N$ degrees of freedom (DOFs) can be written in the standard matrix form as follows:

$$\begin{bmatrix}\mathbf{M} & \mathbf{\Phi}_{\mathbf{x}}^{\mathrm{T}} \\ \mathbf{\Phi}_{\mathbf{x}} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\ddot{\mathbf{x}} \\ \boldsymbol{\lambda}\end{bmatrix} = \begin{bmatrix}\mathbf{F} \\ \boldsymbol{\gamma}\end{bmatrix} \tag{9}$$

where $\boldsymbol{\lambda}$ is Lagrange multiplier.

## 4. Case study

### 4.1. Experiment Setup

The HVAC test bed used in this study is illustrated in Figure 4. The test bed consists of an impeller, motor, and a belt-pulley system. The impeller is a rotating component equipped with a series of blades that accelerate and direct the airflow toward the fan's exhaust. It is enclosed within a housing that directs the airflow and provides a channel for the air to exit the fan. The pulley is connected to the motor and fan shaft, and the motor's rotation transmits power through the belt to turn the fan. The motor is rated at 1800 rpm, and the tension can be adjusted by altering the distance between each pulley, denoted as $d$.

Figure 4. Experimental HVAC test bed with a belt-pulley transmission system

Five different center distances, denoted as $d_0$ to $d_4$, were examined. These distances correspond to various belt loosening conditions and are summarized in Table 1.

Table 1. Center distances and belt conditions

| Center distance | Condition |
|---|---|
| $d_0$ | Healthy belt |
| $d_1$ | Weak belt looseness |
| $d_2$ | Moderate belt looseness |
| $d_3$ | Strong belt looseness |
| $d_4$ | Critical belt looseness |

### 4.2. Simulation Setup

To construct a digital twin model, a simulation model was developed using RecurDyn as depicted in Figure 5. RecurDyn provides a framework for modeling HVAC systems based on MBD theory, as detailed in Section 3. The model parameters were updated by comparing the simulation results with the experimental slip results. The contact force model employed stiffness where $K = 1000 N/m$ and damping $D = 10 Ns/m$, while the friction model employed a friction coefficient $\mu = 0.7$. In order to consider the uncertainty, the analysis was performed in the range of 1% of the friction coefficient.

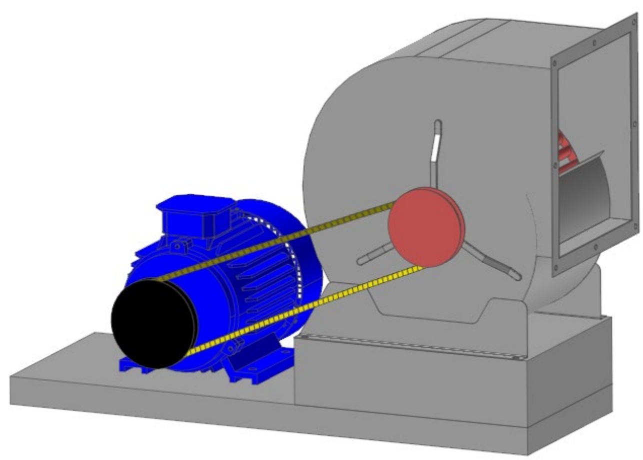

Figure 5. The simulation model of HVAC system using RecurDyn

### 4.3. Results

To verify the framework for constructing the digital twin, the slip distributions of the experiment and the simulation were compared. The comparison results are presented as a box plot in Figure 6. As can be observed from the box plot, the simulation distributions can be confirmed within the experimental distributions. Furthermore, the slip range in the experiment with an increase in the severity of belt looseness is also evident and can be observed in the simulation. The average values of the belt slips of the experiments and simulations according to the center distance corresponding to the various belt loosening conditions are summarized in Table 2. The error of slip between the experiment and simulation according to the severity of the belt looseness is within 5%. This simulation model demonstrates a good correlation with the experimental results and indicates the possibility of developing a digital twin model to determine the slack of the belt.

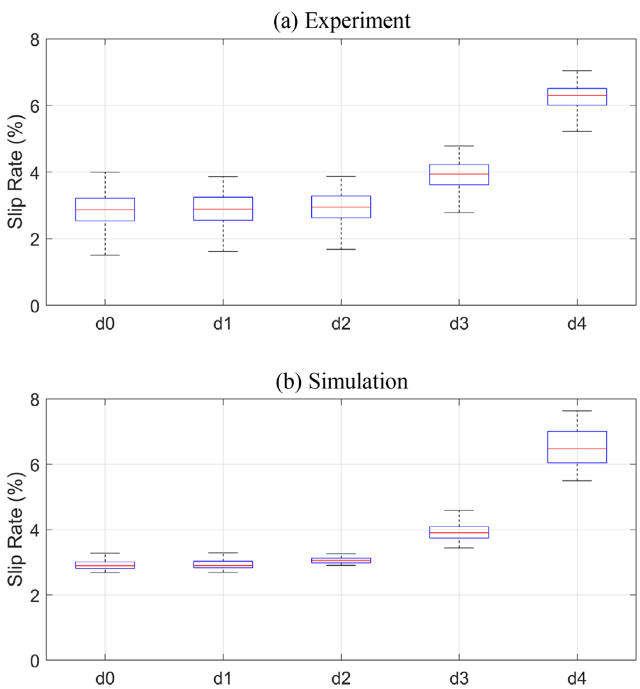


Figure 6. Comparison results of slip distribution between (a) experiment and (b) simulation

Table 2. Comparison results of average slip between experiment and simulation

| Center distance | Average slip (%) | | Error (%) |
|---|---|---|---|
| | Experiment | Simulation | |
| $d_0$ | 2.8582 | 2.9181 | 2.09 |
| $d_1$ | 2.8805 | 2.9247 | 1.54 |
| $d_2$ | 2.9398 | 3.0569 | 3.98 |
| $d_3$ | 3.9109 | 3.9160 | 0.13 |
| $d_4$ | 6.2492 | 6.5122 | 4.21 |

## 5. Conclusion

This paper outlines the development of a simulation technique aimed at constructing a digital twin model that accurately detects belt looseness in HVAC systems. This study was evaluated by comparing slip results obtained from HVAC system experiments with simulation models. The findings demonstrate that the simulation model effectively captures the slip distribution during the four-stage belt loosening experiment. Therefore, simulation technology can provide extensive data on belt looseness at various stages, which can be utilized to develop diagnostic models for identifying belt looseness in HVAC systems.

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