

Research on Rigid-flexible Coupling Dynamic Modeling and Dynamic Characteristics Based on Tremmie Pipe

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Abstract: The tremmie pipe is the key structural component of the rubble leveling ship. Its vibration affects the laying accuracy of the rubble leveling ship. The 3D structural model of the tremmie pipe ship is established with the help of the 3D modeling software SolidWorks, and the tremmie pipe is flexible by ANSYS. The rigid-flexible coupling dynamics model is built in ADAMS. Apply constraints and external excitation of the pipe end, carry out modal analysis and dynamic simulation analysis on the model, study the dynamic characteristics of the tremmie pipe during the tremmie pipe process, provide the basis for structural vibration control, and have guiding significance for the optimal design of the tremmie pipe.

Keywords: Rubble leveling ship, Rigid-flexible coupling, Modal analysis, ADAMS.

1. Introduction

The rubble leveling ship is a kind of marine equipment that can level rock in deep water. It was developed in the 1960s., the core technology of rock leveling is mainly concentrated in a few developed countries, such as Japan, the United Kingdom and the United States [1]; my country's research on deep-water rock leveling technology lags behind that of developed countries, and a lot of research work began in the late 1970s. The "Jinping No.1" developed and manufactured by my country in Nantong Base has successfully completed the rock leveling operation of the foundation bed of the 33-section immersed tube of the Hong Kong-Zhuhai-Macao Bridge in March 2017 [2].

Although the rubble leveling ship have been used in practical engineering, there are few references for theoretical analysis of the rubble leveling ship. Most of the problems in practical engineering are dynamic problems. With the development of multi-flexible body dynamics, many virtual prototyping technologies have emerged [3-6], which provide reliable analysis techniques for analyzing engineering problems.

The tremmie pipe is the key structural component of the rubble leveling ship, and its vibration affects the laying accuracy of the rubble leveling ship. In this paper, ADAMS and ANSYS software are used for joint simulation to establish a rubble leveling ship with flexible tremmie pipe. The rigid-flexible coupling dynamic model is used to calculate the nodal stress distribution of the tremmie pipe and the acceleration curve of the pipe end, and analyze the dynamic response of the tremmie pipe under the action of external loads.

2. Rigid-flexible Coupling Theory

Rigid-flexible coupled multi-body dynamics system is a system composed of multiple rigid bodies and multiple flexible bodies connected in a specific system. It is a natural extension of the multi-rigid-body dynamic system. The dynamics of the rigid-flexible coupling system mainly studies the interaction between the elastic deformation generated by the internal or external forces of the system and the spatial motion within a specific range after the key components are

flexible, and the dynamic effects caused by this relationship. This dynamic effect is an essential characteristic of a rigid-flexible coupled multi-body dynamics system, making it not only different from the multi-rigid body dynamics system, but also from the structural dynamics.

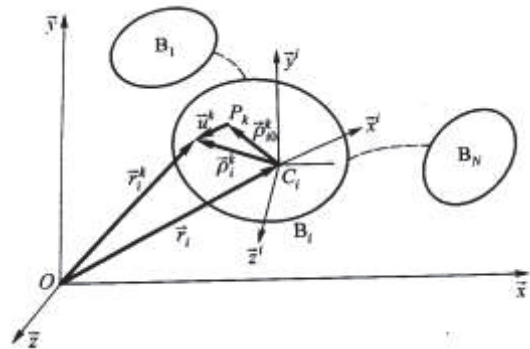


Figure 1. Multi-flexible body system in space motion

As shown in Figure 1, for a flexible body system composed of N flexible bodies, a common reference datum is defined for the system, denoted as $\vec{e} = (\vec{x} \ \vec{y} \ \vec{z})^T$, and the reference point is O . Take a point C_i on the flexible body $B_i = (i = 1, \dots, N)$ before deformation as a reference point to establish a floating reference, denoted as $\vec{e}^i = (\vec{x}^i \ \vec{y}^i \ \vec{z}^i)^T$, the vector of C_i relative to datum O is denoted as \vec{r}_i , and the coordinate matrix in \vec{e} is $r_i = (x_i \ y_i \ z_i)^T$.

The configuration of the flexible body B_i is determined by the displacement coordinate matrix \vec{r}_i of the floating datum point, the attitude coordinate matrix π_i of the floating datum about the common datum, and the modal coordinate matrix a_i of the flexible body B_i , which constitute the configuration coordinate matrix of the flexible body B_i , which is denoted as

$$q_i = (r_i^T \quad \pi_i^T \quad a_i^T)^T \quad (i=1, \dots, N) \quad (1)$$

These N matrices constitute the coordinate array of the flexible multi-body system, which is denoted as

$$q = (q_1^T \quad \dots \quad q_N^T)^T \quad (2)$$

Let P_k be an arbitrary point on the flexible body B_i , \vec{r}_i^k is the vector radius of point P_k relative to datum O , \vec{p}_i^k be the vector radius of P_k relative to C_i , and \vec{u}_i^k be the deformation displacement vector

$$\vec{r}_i^k = \vec{r}_i + \vec{\rho}_i^k, \vec{p}_i^k = \vec{\rho}_{i0}^k + \vec{u}_i^k \quad (3)$$

Find the first derivative of equation (3) with respect to time, we get

$$\dot{\vec{r}}_i^k = \dot{\vec{r}}_i + \vec{\omega}_i \times \vec{\rho}_i^k + \dot{\vec{u}}_i^k = \dot{\vec{r}}_i - \vec{\rho}_i^k \times \vec{\omega}_i + \dot{\vec{u}}_i^k \quad (4)$$

Where $\dot{\vec{u}}_i^k$ is the derivative of the deformation displacement vector with respect to time on the floating reference?

Find the second derivative of equation (3) with respect to time, we get

$$\ddot{\vec{r}}_i^k = \ddot{\vec{r}}_i - \dot{\vec{\rho}}_i^k \times \vec{\omega}_i + \vec{\omega}_i \times (\vec{\omega}_i \times \vec{\rho}_i^k) + 2\vec{\omega}_i \times \dot{\vec{u}}_i^k + \ddot{\vec{u}}_i^k \quad (5)$$

3. Modeling of Rigid-flexible Coupled System for Virtual Prototype of The Rubble Leveling Ship

3.1. Rigid Body Model Creation

There are different methods for establishing the rigid body model. Considering that the model of the rubble leveling ship is relatively complex and the ADAMS solid modeling function is relatively weak, the 3D software SolidWorks is used to establish the 3D assembly model of the rubble leveling ship. The model is mainly composed of hull, mobile cart, cage, mobile trolley and other components. In the process of modeling, some details are appropriately simplified, ignoring external installation equipment, etc., only the main frame of the model is established.

The model is divided into four main assemblies, such as the hull, the mobile cart, the cage, and the mobile trolley. They are assembled in SolidWorks according to the drawings, and each assembly is shown in Figure 2.

3.2. The Establishment of Flexible Body Model

At present, most finite element software supports the output of mnf files, such as Nastran/Hypermesh/ANSYS, etc. In this case, ANSYS is used to divide it into meshes. First, create and save the tremmie pipe model in SolidWorks as an x_t file, then import the file in ANSYS, set the element type,

material properties, and real constants, and use the mesh tool to mesh the tremmie pipe. The resulting mesh is shown in Figure 3.

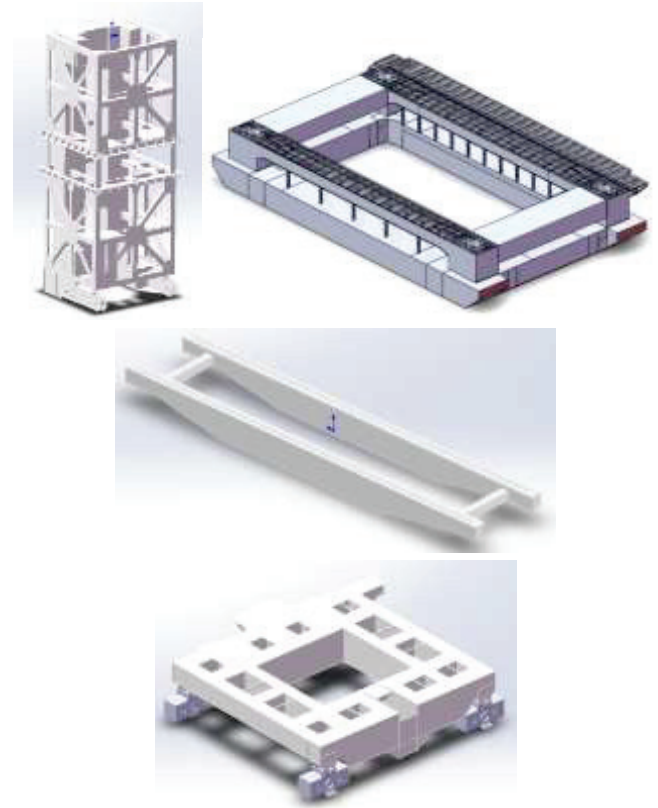


Figure 2. Rigid body model created by SolidWorks

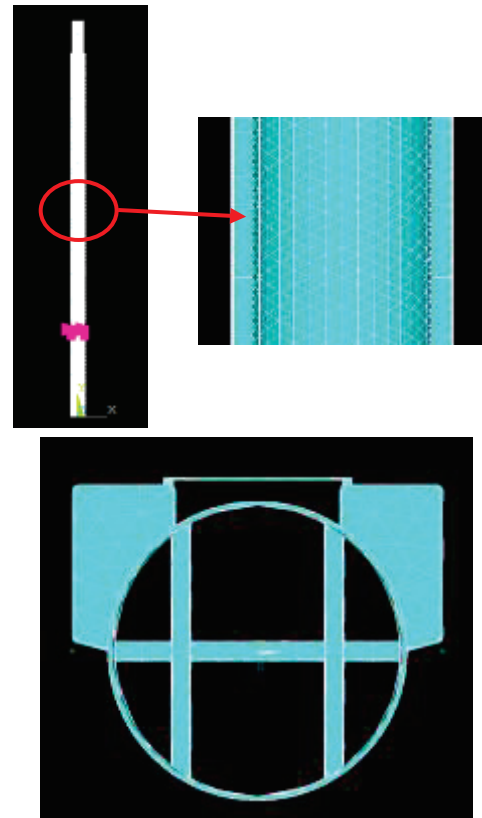


Figure 3. Front and top views of the finite element model of the tremmie pipe

4. Rigid-flexible Coupling Dynamics Simulation of The Rubble Leveling Ship Based on Tremmie Pipe Flexibility

Import the rigid body model and the flexible tremmie pipe into ADAMS through the ADAMS data interface, complete the assembly and correction of the model in ADAMS, impose constraints and drive to complete the creation of the rigid-flexible coupling model of the rubble leveling ship. The virtual prototype model of the rubble leveling ship is shown in Figure 4.

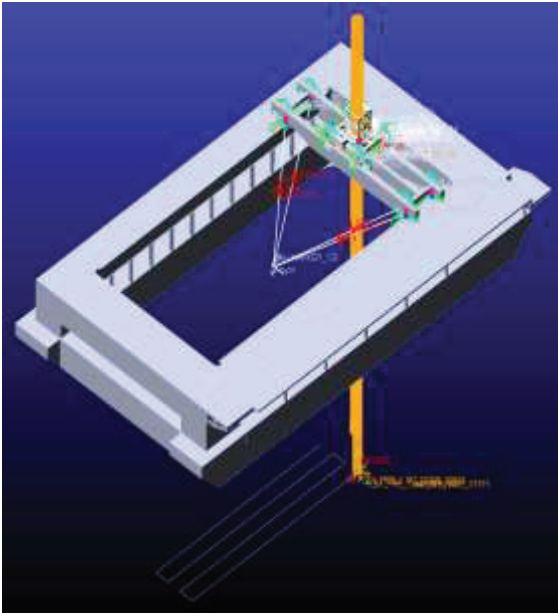


Figure 4. The virtual prototype model of the rubble leveling ship

4.1. Modal Shape Analysis

(1) Modal analysis of the tremmie pipe in the free state

Modal refer to the natural vibration characteristics of mechanical structures, each of which corresponds to a specific frequency and modal shape. Modal analysis is necessary to analyze whether the scraping force generated by the tremmie pipe and the laying cushion will cause resonance during the rock leveling of the rubble leveling ship.

The first 6 frequencies of the tremmie pipe are very small, which can be equivalent to the mode of the rigid body. This paper mainly considers the frequencies from the 7th to the 10th order, as shown in Table 1.

Table 1. The frequency of tremmie pipe

Numble	Frequency (Hz)
7	1.9396864788
8	2.2855813317
9	5.3426003087
10	6.3133274595

The mode shapes corresponding to each order are shown in Figure 5.

(2) Modal analysis of rubble leveling ship under restraint

The modal of the rubble leveling ship in the constrained state has a total of 44 orders, as shown in Figure 6 through the scatter distribution drawing. The most effective frequency is the 9th order, which is 0.5111194Hz, and its mode shape is shown in Figure 7.

By comparing the rubble leveling ship frequency

0.5111194Hz under the constraints, it is not equal to the natural frequency of the tremmie pipe 1.9396864788Hz, so the tremmie pipe does not reach resonance due to external excitation during the rock leveling.

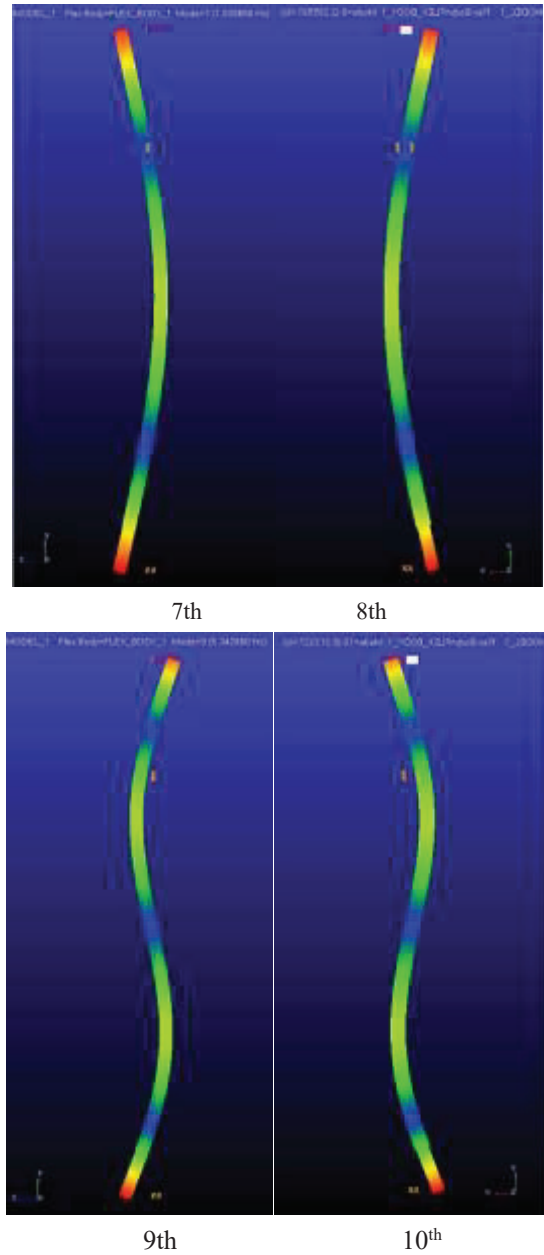


Figure 5. Frequencies of the 7th to 10th orders of the tremmie pipe

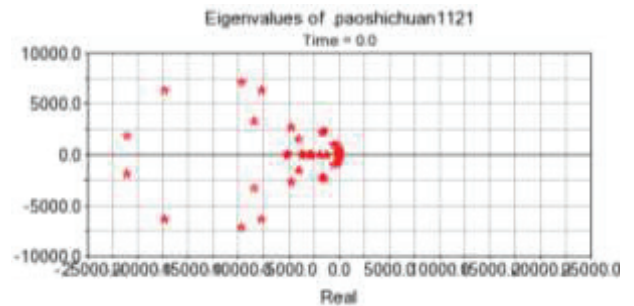


Figure 6. Frequency distribution of the rubble leveling ship under constraints

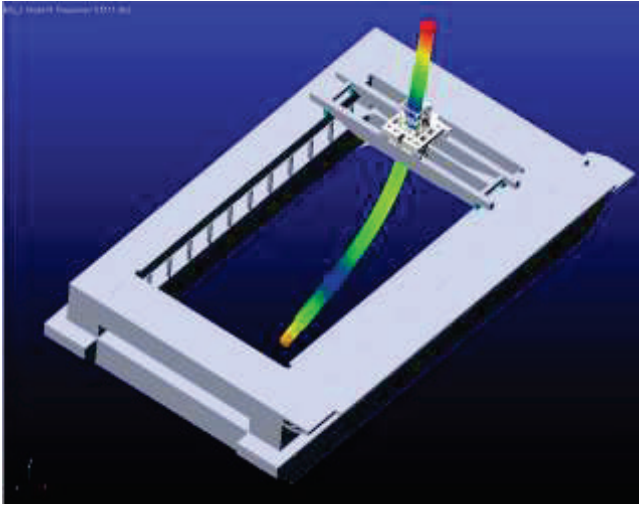


Figure 7. Modal shapes of the 9th order of the rubble leveling ship

4.2. Application of Scraping Force at The End of Tremmie Pipe

In the process of rock leveling operation, the paved rock will produce a scraping force opposite to the direction of movement of the tremmie pipe end when the tremmie pipe is continuously moving forward. The data of this part of the scraping force is calculated by the simulation of the rock leveling in the discrete computing software EDEM.

Here, when the cart is running at a constant speed of 2.6m/min and the stone cushion is 30cm high, the scraping force curve of the pipe end is shown in Figure 8.

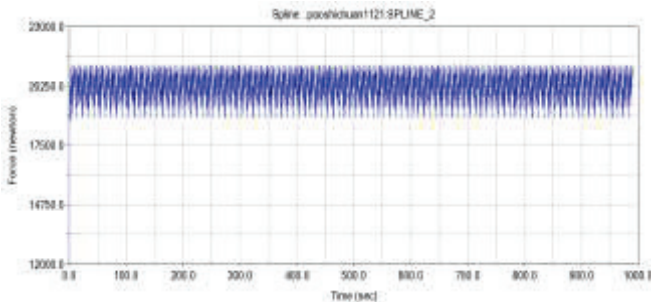


Figure 8. Scraping force curve of tremmie pipe end

The ADAMS/Solver module is a solver for ADAMS that provides various solution options. For dynamic differential equations, different integration algorithms need to be selected according to the actual model. GSTIFF is the most stable integral solver officially provided by ADAMS, and selects the I3 integral equation in this paper. The I3 integral format is as follows:

$$\left. \begin{aligned} \dot{P} - \frac{\partial T}{\partial q} + \Phi_q^T \lambda + H^T F &= 0 \\ P &= \frac{\partial T}{\partial \dot{q}} \\ u &= \dot{q} \\ \Phi(q, t) &= 0 \\ F &= f(u, q, t) \end{aligned} \right\} \quad (5)$$

The cart runs at a speed of 2.6m/min, which is obtained by solving I3, and the running process is shown in the Figure 9.

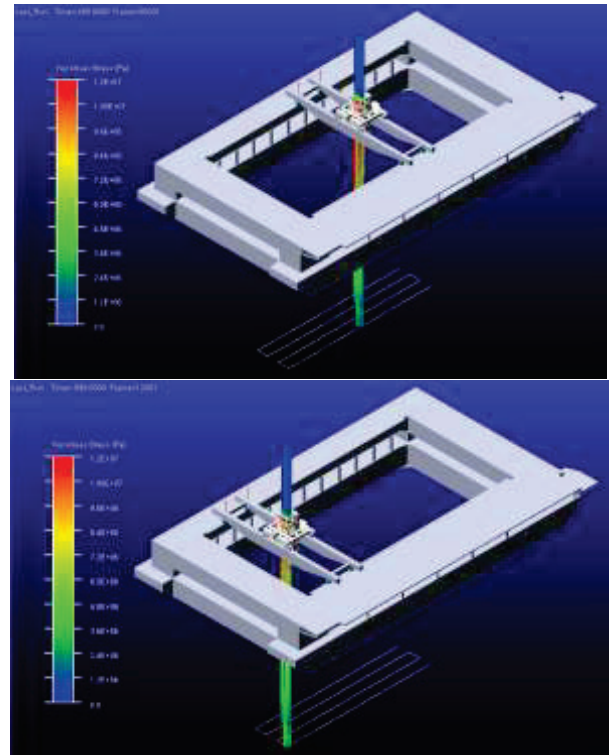


Figure 9. Motion process diagram of rigid-flexible coupling dynamic simulation of rubble leveling ship

The 10-node information of the maximum stress of the tremmie pipe, in which you can see the number, location and stress value of each node. As shown in Figure 10.

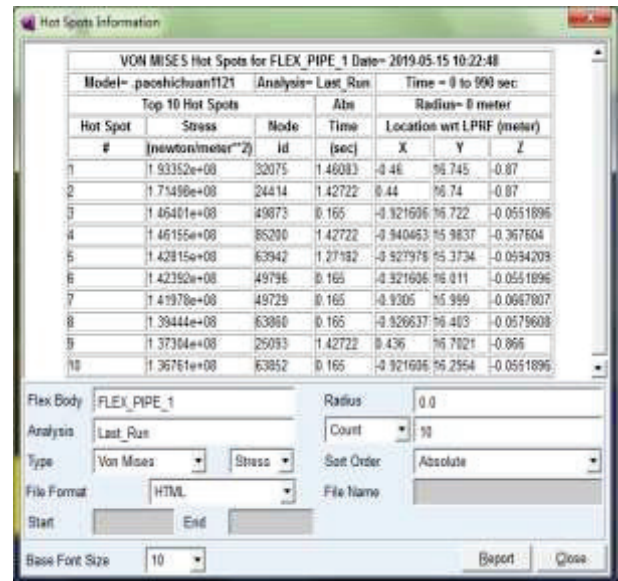


Figure 10. The 10-node information for the maximum stress of the tremmie pipe

During the process of the cart running a ridge at 2.6m/min, the stress curve of the pipe end node 91 of the tremmie pipe is shown in Figure 11, and the vertical acceleration curve of the pipe end of the tremmie pipe is shown in Figure 12.

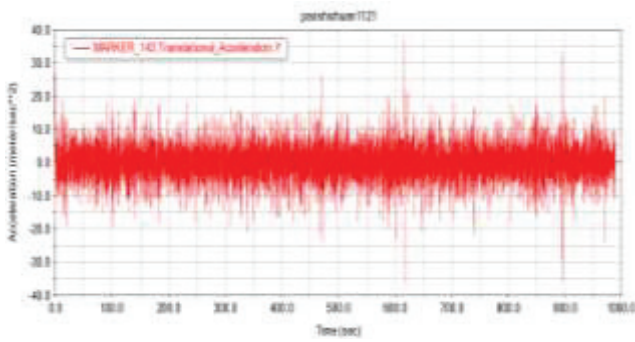


Figure 11. Stress curve of tremmie pipe node 91

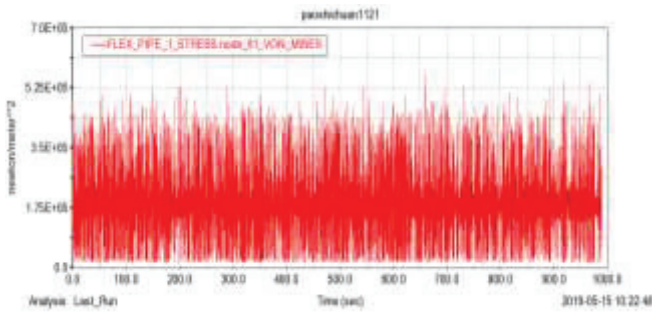


Figure 12. The vertical acceleration curve of the pipe end of the tremmie pipe

From Figures 11 and 12, it can be seen from the displacement curve that the stress of the node 91 at the pipe end fluctuates violently, and the acceleration curve alternates violently between positive and negative near the 0 position.

It can be seen from the simulation results that the pipe end of the tremmie pipe will vibrate significantly in the vertical direction under the influence of the scraping force.

5. Summary

This paper verifies from modal analysis that, regardless of electrical control and external excitation, the external

excitation frequency of the rubble leveling ship is not equal to the natural frequency of the tremmie pipe, and the resonance between the tremmie pipe and the external excitation will not occur.

Through the rigid-flexible coupling simulation of the flexible tremmie pipe, it can be seen that there is strong vibration at the pipe end of the tremmie pipe, which provides a theoretical reference for actual construction and has important reference significance for improving the actual operation accuracy of the rubble leveling ship.

The research in this paper only considers the flexibility of the tremmie pipe, and the next step will be to study the flexibility of the cage, cart, and hull according to the actual situation.

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