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Multibody-dynamics approach for modelling highly-flexible structures in aerospace engineering

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Abstract

Developing numerical models to solve the dynamics of highly-flexible structures is challenging, especially in aerospace engineering where the fluid-structure interaction may have many complex effects. Some models based on the coupling of Computation Fluids Dynamics (CFD) and Computational Structural Dynamics (CSD) have been developed to solve this type of problem. However, these models usually require a large amount of computer resources. The multibody-dynamics approach may offer reduced-order modelling methods with lower number of degrees of freedom and more cost-effective. This work presents the development of this kind of model and the applications to several highly-flexible structures in aerospace engineering and other similar research areas. The presentation also shows numerical programs that were developed based on in-house codes and software solvers for flexible structures simulation. These models and programs were validated against experimental data.

Keywords: Multibody dynamics, fluid-structure interaction, flapping wings, piezoelectric beam

1. Introduction

Simulating the responses of highly flexible structures in aerospace systems is challenging due to their complex natures [1]. For this type of simulation, aerodynamic and structural dynamics solvers have to run in parallel and are coupled for the fluid-structure interaction problem. There have been a number of methods for highly-flexible structures dynamics simulation in aerospace engineering [2-4]. Most of them were developed based on nonlinear finite-element-analysis (FEA) solvers, which require a large number of degrees of freedom models. The multibody-dynamics (MBD) approach can offer simpler models for geometrically-nonlinear structures. Modelling structures with the MBD approach often require less degrees of freedom compared to FEA-based methods. Additionally, the MBD approach tends to be more efficient while combining the structural responses with the dynamics behaviors of the whole system.

This paper presents the development and applications of the MBD approach for several aerospace structures. The simulations were conducted based on the combination of in-house codes and software solvers.

2. Methodology

For beam-like structures, the lumped-mass method is applied; torsion springs are used to connect discrete bodies. The stiffness coefficients of these springs may be determined from experiments or data from corresponding FEA models. Figure 1 shows the modelling of an insect-wing structure by the MBD approach.

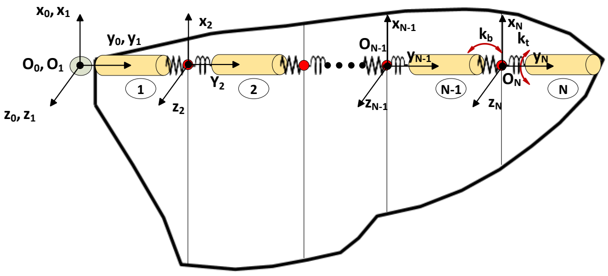

Fig. 1 Lump-mass method to model an insect-wing structure by the MBD approach

For membrane structures, firstly, an FEA mesh is replaced by a system of masses and extension springs (Fig. 2). The stiffness coefficients of the springs are determined by based on the principle of strain-energy equivalence [5].

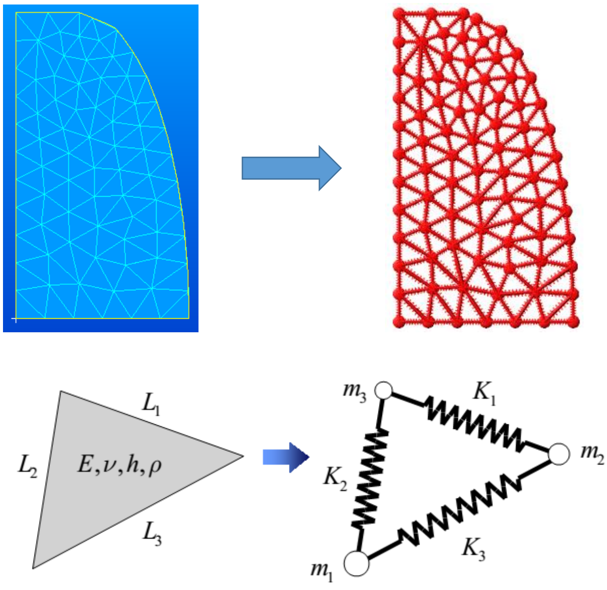

Fig. 2 Application of the MBD approach to model membrane structures

The Lagrangian method is applied to derive differential equations characterizing the dynamics of the MBD system, which can be written in the matrix form as follows:

$$\boldsymbol{M}(\boldsymbol{\Phi},\dot{\boldsymbol{\Phi}},t)\ddot{\boldsymbol{\Phi}} + \boldsymbol{H}(\boldsymbol{\Phi},\dot{\boldsymbol{\Phi}},t) = \boldsymbol{Q}(\boldsymbol{\Phi},\dot{\boldsymbol{\Phi}},t) \qquad (1)$$

where $\boldsymbol{\Phi}$ is the vector of generalized coordinates.

Aerodynamic loads can be obtained by quasi-steady or unsteady models and applied to the system in the form of external forces and moments (Fig. 3). For each time step, the prediction-correction method is used to obtain the converged solution. In some cases, due to the complex nature of the fluid-structure interaction problem, computers may need to run tens or hundreds of iterations to obtain the converged state within each time step.

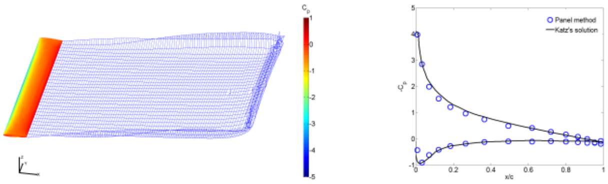

Fig. 3 Unsteady panel method for aerodynamic simulation

3. Applications to structural dynamics analyses

3.1. Insect-like wing structures

Figure 4 shows the simulation results for the hawkmoth wing and an insect-like flapping wing. These beam-like structures were modelled by rigid bodies connected by torsion springs to emulate the bending and torsional deformations of the structures. The unsteady panel method was used and combined with the MBD model for the fluid-structure interaction simulation [6].

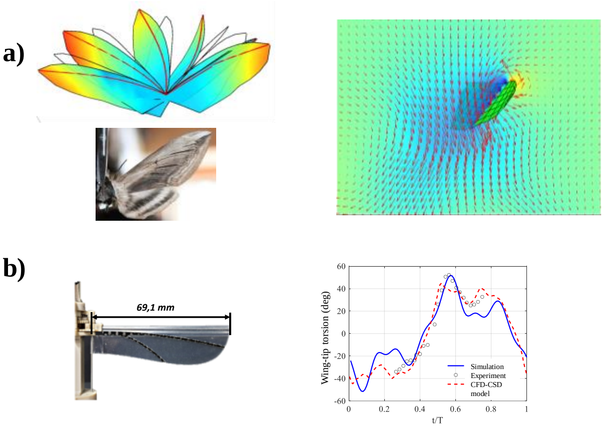

Fig. 4 Simulation of the hawkmoth wing (a) and an insect-like flapping wing (b)

The simulation results with the MBD approach show good agreement with experimental data and those from higher-order numerical methods.

3.2. Membrane structures

For membrane structures, a quasi-steady aerodynamic method was used to integrate into the MBD solver. The thrust and power obtained by the MBD solver was close to experimental data provided by Ghommem et al. [7].

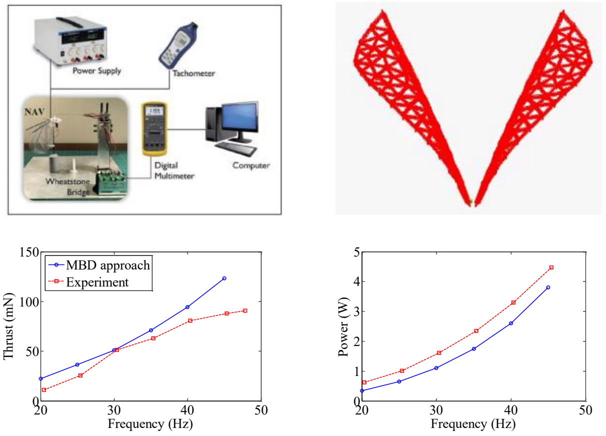

Fig. 5 Simulation of membrane flapping wings

3.3. Piezoelectric structures

The MBD approach can be used for piezoelectric structures, in which piezoelectric loads may be modelled as external forces and moments. Figure 6 shows the comparison of the frequency response function obtained by the MBD model with that from MSC NASTRAN for a piezoelectric beam [8]. It is seen that the MBD model can capture most of the resonance peaks.

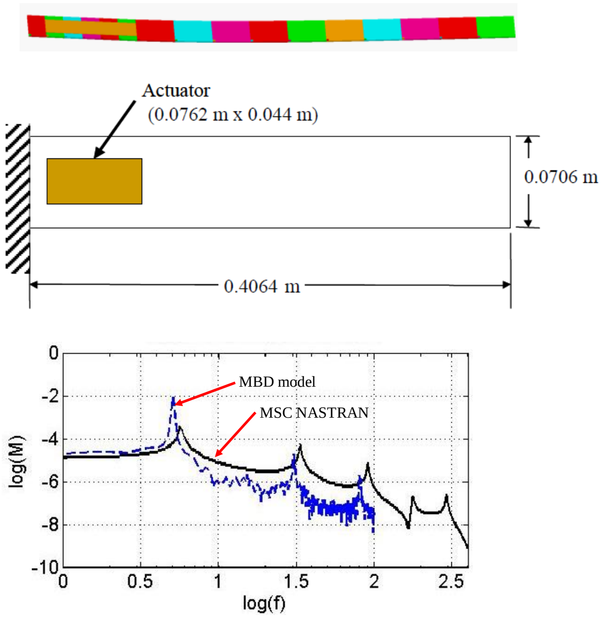

Fig. 6 Simulation of membrane flapping wings

3.4. Other structures

Due to the similarity in terms of physics between air and liquid. The MBD approach has been applied to underwater systems such as fish and eel robots (Fig. 7).

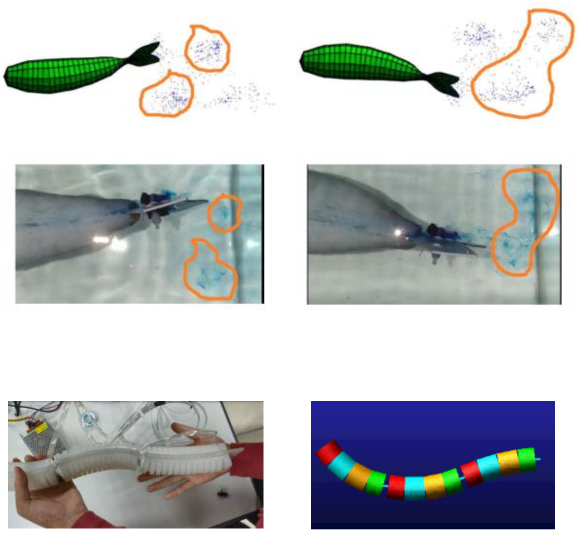

Fig. 7 MBD approach for the simulation of fish and eel robots

Conclusions

The MBD approach for the simulation of highly flexible structures can be an effective option in many cases due its simplicity compared to other conventional methods. MBD models can accurately analyze large deformation with a lower number of degrees of freedom. Moreover, the MBD approach offers an easier way to model fluid-structure-motion interaction when we are interested not only in the behavior of a structure but also in the dynamics of the whole system.

Acknowledgement

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