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TIME-ACCURATE SIMULATION OF A MANOEUVRING AEROELASTIC DELTA WING AT HIGH ANGLE OF ATTACK

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Abstract

The central challenge is to simulate the time-accurate aeroelastic coupling of the flexible aircraft body with a non-linear aerodynamic solver in guided or free-to-roll manoeuvres. The approach described in this paper is one of two investigated variants in the DLR project SikMa and is characterized by the use of a multibody system (MBS) to account for the elastic structure as well as the flight mechanics and its loose coupling to the computational fluid dynamics (CFD) software. The exchanged data is interpolated with a general mesh coupling tool and transferred through an internet socket allowing a distributed computational environment.

The initial test applications are coupled simulations of the manoeuvring elastic wind tunnel model of a generic delta wing in guided motion.

Nomenclature

α	Angle of attack
θ	Pitch angle
C_D	Drag coefficient
C_L	Lift coefficient
C_{mx}	Moment coefficient x-axis
C_{my}	Moment coefficient y-axis
C_p	Pressure coefficient
F_z	Force z-direction
M_x	Moment x-axis
Ma	Mach number
f	Frequency
t	Time

1 Introduction

The project SikMa has been implemented to develop a simulation platform in a distributed computational environment for the time-accurate simulation of an elastic aircraft with moveable control surfaces manoeuvring at high angle of attack. SikMa, i.e. simulation of complex manoeuvres, is an interdisciplinary project which involves the DLR institutes of aerodynamics, aeroelasticity, flight systems and software technology as well as industrial partners. The final simulation results from the project will be verified against experimental and flight test data.

The core requirements for the simulation setup comprise the correct mechanical modeling of the rigid and elastic body, the precise description of the complex flow around the delta wing including separation and vortex burst, as well as the time- and energy-correct description of the aeroelastic coupling.

Earlier simulation results [1] for a rigid model of a generic delta wing have been compared to measurements from a transonic wind tunnel. The used wind tunnel setup is depicted in Fig. 1 and comprises the model sting with attached roll drive unit and the generic delta wing. The comparison to the experimental results of the guided and free-rolling delta wing shows potential for improvement. Thus, the introduction of an elastic model changes the simulation from unsteady aerodynamics with combined flight mechanics for the rigid structure into a dynamic aeroelastic problem with combined flight mechanics, as shown in Fig. 2. This fluid-structure-flight mechanics coupling has to consider the linear elastic and non-linear inertial coupling terms from the rigid body motion, here combined in a single software package by using an elastic multibody system.

The current simulations comprise guided manoeuvres of the elastic delta wing on the elastic sting with CFD in Euler mode, while the upcoming investigations will focus on free-roll manoeuvres. The control surfaces of the delta wing are in a fixed position for these simulations.

2 Simulation Tools and Models

2.1 Computational Fluid Dynamics

The behaviour of the fluid flowing around the object of interest is simulated with the Tau-Code, a CFD tool developed by the DLR Institute of Aerodynamics and Flow Technology [2]-[4]. The Tau-Code solves the compressible, three-dimensional, time-accurate Reynolds-Averaged Navier-Stokes equations using a finite volume formulation. The Tau-Code is based on an unstructured-grid approach, which makes use of the advantages that hybrid grids offer in the resolution of viscous shear layers near walls, and the flexibility in grid generation offered by unstructured meshes. A dual-mesh approach is used in order to make the flow-solver independent from the cell types used in the initial grid.

The Tau-Code consists of several different modules, among which are:

- The Preprocessor module, which uses the information from the initial grid to create a dual-mesh.
- The Solver module, which performs the flow calculations on the dual-mesh and applies guided rigid-body-motions when specified.
- The Deformation module, which propagates the deformation of surface coordinates to the surrounding grid.
- The Post-processing module, which is used to convert Tau-Code result files to formats usable by popular visualization tools.

In the Solver module, several upwind schemes, as well as a central scheme with artificial dissipation, are available for the spatial discretisation. The Solver module can be executed in three modes: Euler, Navier-Stokes 1-Equation turbulence modeling and 2-Equation turbulence modeling. The results shown in this paper are all based on the Euler mode of execution. For steady calculations, an explicit multistage Runge-Kutta time stepping scheme is used. For time accurate computations, an implicit dual-time stepping approach is used. The Tau-Code is parallelized using grid partitioning, and a multi-grid approach is used in order to increase the performance.

2.2 Multi Body Dynamics

The multibody system SIMPACK [5]-[6] is used to simulate the mechanical model with respect to the large deformation of the rigid motion and the small deformations of the elastic motion. The development of this simulation package was started by the DLR and later out-sourced to INTEC for further development and commercial distribution. This MBS provides all the non-linear 2nd order inertial coupling terms and allows the setup of elastic simulation models via a modal approach for linear finite element models. Beyond this classical scope of MBS features, a number of interfaces for model import and export to standard tools in the fields of computer aided engineering (CAE) and control engineering (CACE) are implemented and allow mechatronic design. SIMPACK is an accepted standard engineering tool in the automotive and railway design.

The functionality in terms of flight mechanics allows the definition of the investigated wind tunnel manoeuvres. Modules and interfaces of special interest for this application are:

- Finite element analysis (FEA) interface, here NASTRAN
- Co-simulation interface for data exchange to non-standard partner codes, here CFD Tau
- Interactive, graphical user interface for model setup and animation of kinematics and results

A more detailed statement about features for the application of SIMPACK in aeronautical engineering is found in [7].

2.3 Mesh Coupling Software

The spatial coupling of the structural and the CFD meshes as well as the data transfer between the coupled codes is established by the MpCCI coupling library [8]-[9] that has been developed by Fraunhofer SCAI. MpCCI is a mesh-based parallel code coupling interface using the message passing interface MPICH [10]-[11] for communication between the coupled partner codes and offers different standard coupling and interpolation algorithms which are either node or element based.

The setup of a code coupling with MpCCI requires the following preparations:

- Integration of MpCCI calls in the partner codes
- Specification of the coupling surface in terms of nodes and element geometry to MpCCI
- Common MpCCI input file

The visualising software CCIVIS is a part of the MpCCI software distribution and allows the control of the defined coupling surfaces and the transferred quantities, as depicted in Fig. 3 for coordinate positions of the structural and aerodynamic surface for the generic delta wing. Also a graphical user interface is included for easy setup of the common MpCCI input file.

2.4 Used Models

Approximate span and fuselage length of the wind tunnel model is 0.4 m and 0.55 m, respectively. The actual model used by the CFD code is the delta wing and a short part of the sting represented in a small Euler mesh with tetraeder volume discretisation to achieve short computation times.

The available finite element models are the generic delta wing and the structurally identified wind tunnel sting [12]. For each elastic node of the NASTRAN finite element model, one elastic MBS marker is generated in the SIMPACK FEA interface. These are shown in Fig. 4 after the implementation of the elastic finite element sub-structures into the MBS for the rotating (red marker) and the non-rotating (yellow marker) MBS bodies. Each elastic marker of the rotating body is equipped with one force element and one sensor element which are organized as xyz-components in the coordinate vector Y(t) and the aerodynamic load vector U(t) for MpCCI communication. These components refer to the body-fixed coordinate system as used in the aerodynamic and the mechanical model of the delta wing. Hence, the transferred data can be applied without coordinate transformation during the manoeuvre.

Major model information is summarized in the following table:

	Included Structures	**Overall Model**	**Coupling Surface**
CFD	delta wing, short sting	≈177.000 nodes, ≈1.05e6 tetraeder	≈11.500 surface triangles
MBS	delta wing, long sting	106 marker of elastic wing, 15 marker of elastic sting, 1 degree of freedom for rigid roll motion	94 triangle and 30 quadrilateral elements of elastic wing and added fuselage elements

The original coupling surface defined by the structural model of the delta wing was limited to the wing region, which did not result in satisfactory coupling results. Stepwise improvement could be realized by adding nodes and triangular elements to represent the fuselage and sting parts. These nodes are also added as markers to the multibody model where they have a stiff connection to the elastic markers and send or receive coupling data with the vectors Y(t) and U(t), respectively.

3 Simulation Platform

3.1 Coupling of Tau-MpCCI-Simpack

The multibody system integrates the structural and the flight mechanics model in a single code, each problem representing a small number of degrees of freedom (DOF) and short computation time only. In contrast, the time-intensive and costly CFD-computation is performed in its own environment that is suitable for very large aerodynamic models. Both codes exchange their results at each simulated time step in co-simulation through a TCP/IP socket after MpCCI has interpolated the aerodynamic forces and structural coordinates on the respective partner mesh. The developed communication scheme is presented in Fig. 5.

MpCCI calls are integrated in the CFD mesh deformation tool and the co-simulation interface to the MBS, both are members of the CCIRUN block. The required specification of the coupling surfaces to MpCCI is done by the same codes. Further, the Tau solver and pre-processor are linked by pre- and post-executions of the main MpCCI process to the CCIRUN block. The order of the code executions is, beside the control parameters for the spatial coupling, defined in the MpCCI input file. This bundle of codes is started by executing MpCCI.

The computation of the aerodynamic loads in Tau initiates the coupled computation and acts as master of the co-simulation. SIMPACK delivers the new deformations as slave. Whilst the master process has to be started for each time step, the slave process of the MBS cannot be stopped during time integration. This problem is solved with a tailored socket manager on the MBS side and a wrapper to start MpCCI for the desired number of steps.

3.2 Distributed Computation

The realized communication between MpCCI/ Tau and SIMPACK with the data exchange through a TCP/IP internet socket allows the distributed computation in terms of the operating system and the location. The internet socket is a standard feature offered by the SIMPACK co-simulation interface and the MpCCI environment is connected with code 'cci2mbs.c' from Fig. 5.

Since the size of the vectors U(t) and Y(t) depends on the multibody model, the amount of exchanged data is small. Hence, the exchange data can be communicated very efficiently.

4 Simulation Results and Comparison

4.1 Guided Wind Tunnel Manoeuvres

The time-history results of the rigid-body manoeuvre are shown in Fig. 6 to 8, where the direction of the computed hysteresis is indicated by arrows. The manoeuvre is a constant rotation at 5 Hz of the body around its own longitudinal axis. The onflow velocity is at an angle-of-attack of 9^o, at a Mach Number of 0.5. The results show that near to periodic flow conditions have been established by the 3^{rd} cycle of the simulation, and that the normal force and the roll-moment exhibit a sinusoidal behaviour. The pressure-coefficient distribution on the surface of the model is shown in Fig. 9 to 12, at time t of 0.400, 0.452, 0.504, and 0.600 seconds, respectively. In Fig. 9 and 12, the asymmetric pressure distribution can be clearly seen at the beginning and the end of one simulation period. The asymmetry is due to the rotation of the aircraft around its longitudinal axis, which leads to a higher angle of incidence for the downward moving wing, thus influencing the local flow conditions.

The corresponding force results for the coupled simulation with the elastic structure are depicted in Fig. 13 to 15. The results are based on aerodynamic forces computed on the assumption of constant origin and an axis of rotation that does not deform with the model.

The axis of rotation will not be along the body-fixed longitudinal axis of the delta wing model, once the deformation is included. The results of the CFD calculations are given in the reference frame of the axis of rotation. Hence, the angle of attack in Fig. 13 to 15 is the same as for the rigid results. The differences between the results are due to the deformation of the actual grid, which the CFD code receives from the MBS code. Contained within this grid is the change in angle and position due to the elasticity of the model.

4.2 Comparison of Rigid and Elastic Configurations

Due to the elastic deformation of the model, the effective angle of attack has increased, which in turn leads to higher values for the lift and drag coefficients. This tendency is encouraging for future simulations, as it indicates that this initial approach manages to capture those effects that are of interest in such coupled simulations.

The differences observed in the roll moment coefficient will become a more significant point of interest once the free-rotating manoeuvre is simulated. In that case slight changes in roll moment will have a noticeable change in the behaviour of the motion of the model.

5 Conclusions and Outlook

A state-of-the-art loose coupling application including the disciplines of aerodynamics, structural dynamics and flight mechanics has been implemented. The spatial coupling of the CFD code Tau and the multibody system SIMPACK is performed by the commercial mesh-coupling tool MpCCI.

The presented simulation results comprise the guided wind tunnel manoeuvre at a constant rotation for the rigid and elastic configurations of an elastic delta wing on a model sting with fixed controls. The comparison shows an increase in the effective angle of attack for the elastic configuration and related changes in the aerodynamic loads.

The future enhancements will include the free-roll manoeuvre and more complex models with moveable control surfaces.

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Figures

Fig. 1. Generic delta wing and model sting with roll drive unit in the wind tunnel setup

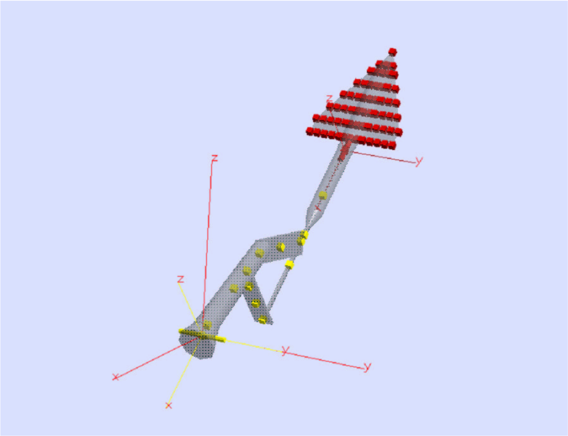

Fig. 4. Generic delta wing and model sting in the MBS

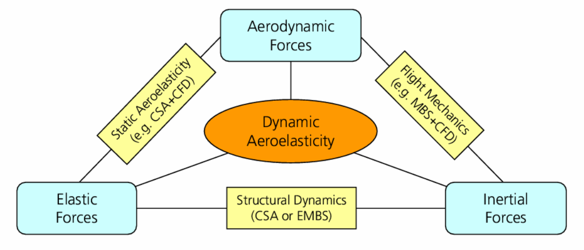

Fig. 2. Dynamic aeroelastic equilibrium

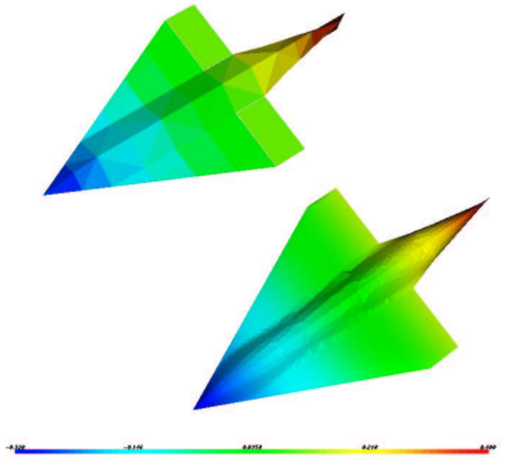

Fig. 3. Control of coupling regions with CCIVIS

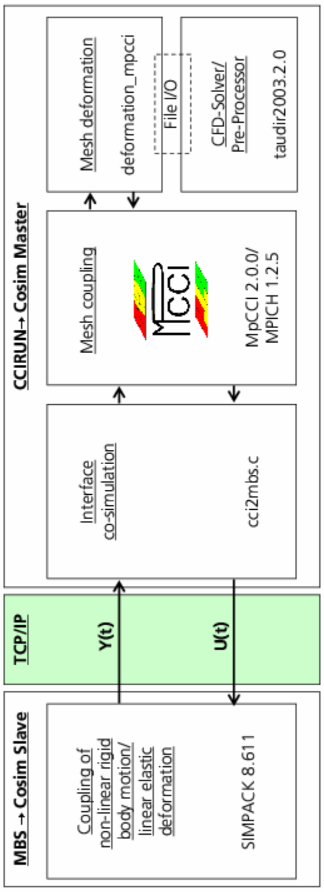

Fig. 5. Communication scheme for co-simulation

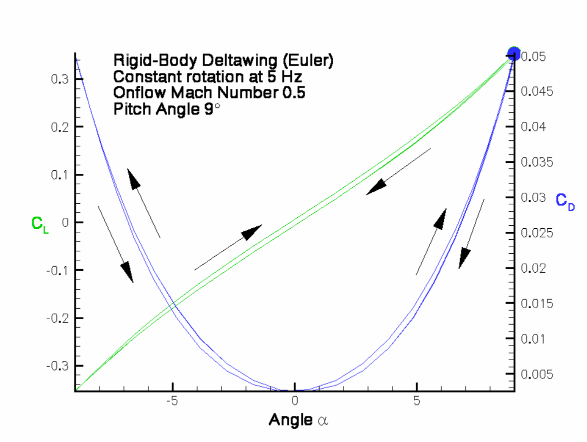

Fig. 6. C_L and C_D vs. α, rigid-body-motion

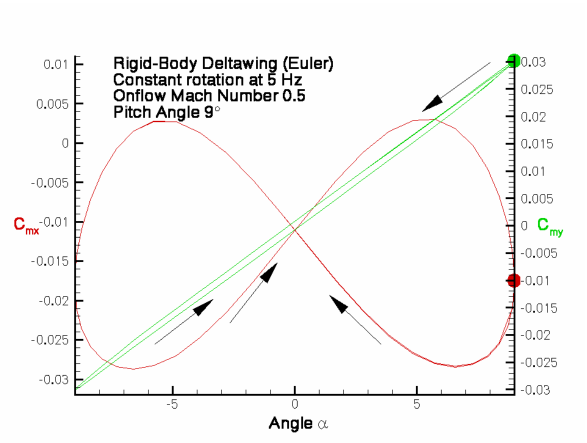

Fig. 7. C_{mx} and C_{my} vs. α, rigid-body-motion

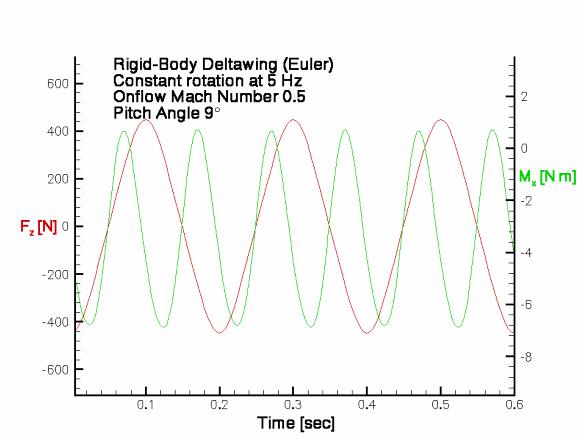

Fig. 8. F_z and M_x vs. Time, rigid-body-motion

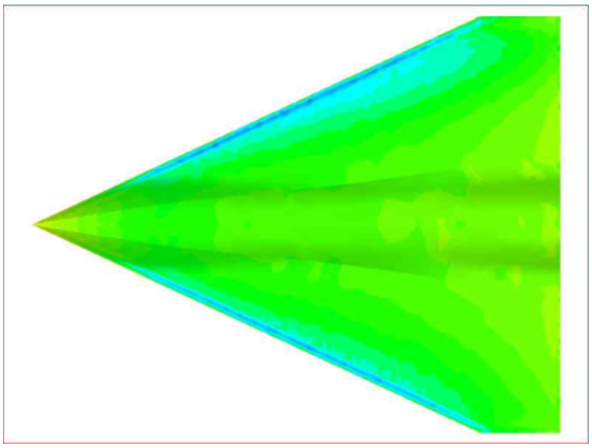

Fig. 9. Surface C_p at t = 0.400 sec., rigid-body-motion

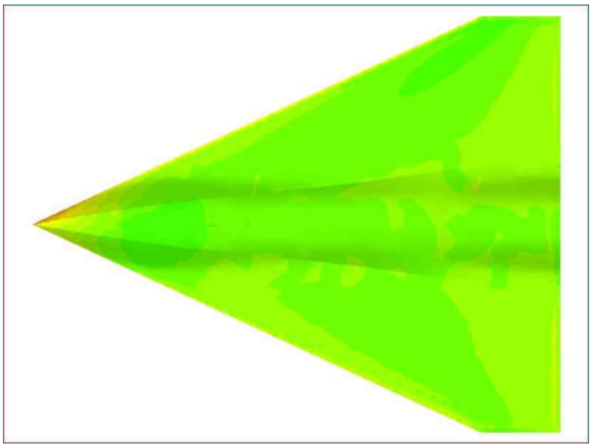

Fig. 10. Surface C_p at t = 0.452 sec., rigid-body-motion

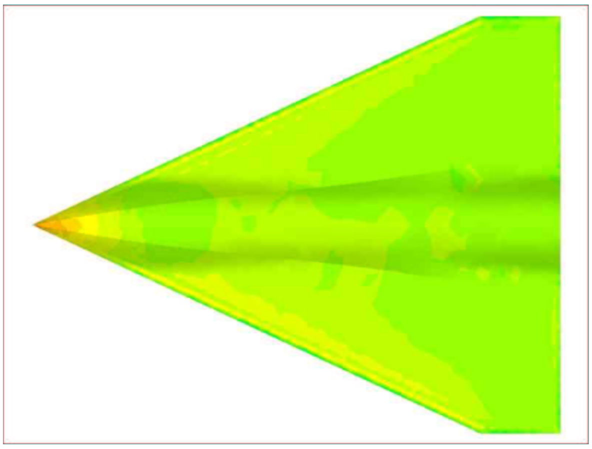

Fig. 11. Surface C_p at t = 0.502 sec., rigid-body-motion

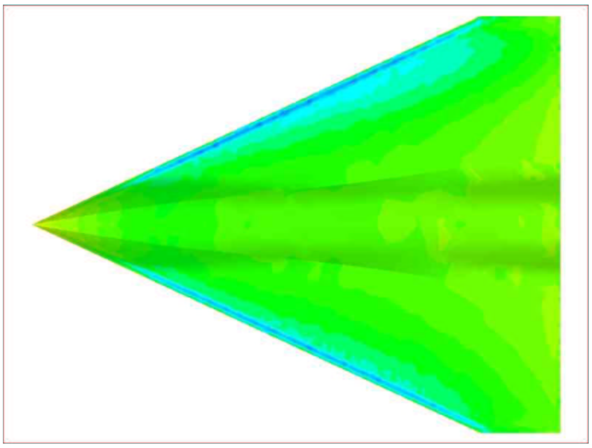

Fig. 12. Surface C_p at t = 0.600 sec., rigid-body-motion

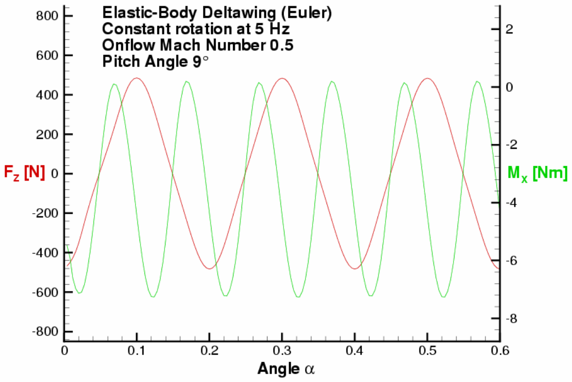

Fig. 15. F_z and M_x vs. Time, elastic-body-motion

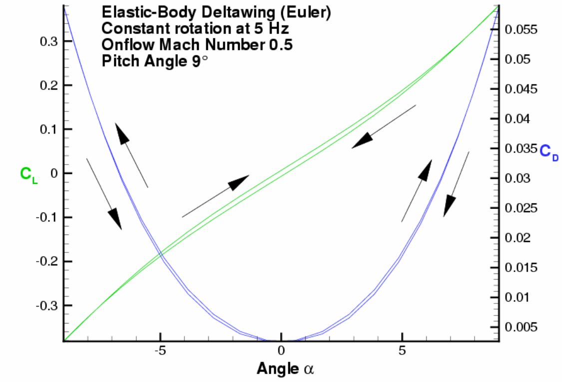

Fig. 13. C_L and C_D vs. α, elastic-body-motion

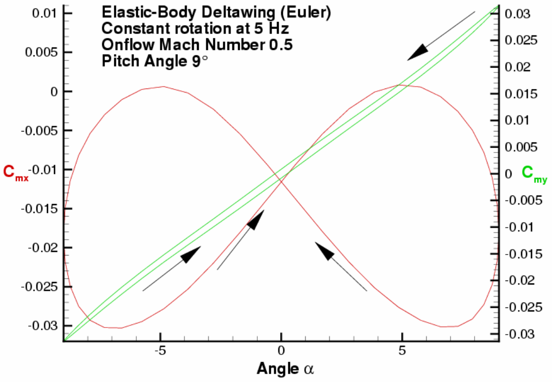

Fig. 14. C_{mx} and C_{my} vs. α, elastic-body-motion