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Computers and Structures 81 (2003) 755–764

Computers & Structures

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FSI analysis in supersonic fluid flow

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Abstract

Aerodynamic control surfaces, i.e. fins, are normally high loaded light weight structures subjected to fluid flow. For minimum weight requirements the fin structure stiffness and the control actuator system stiffness effects must be included in the fin design. In high Mach number flow an interaction between the fluid and the structure is a priori unknown and aeroelastic instability effects may occur. For a 2D-fin profile the fluid–structure interaction will be considered for an increasing fluid velocity up to Ma 2.0 and for stationary flow conditions at Ma 2.0 using ADINA/ADINA-F.

Keywords: Fluid–structure interaction; Aeroelasticity; Fin analysis; Flutter; Unsteady fluid flow; Supersonic fluid flow

1. Introduction

Tremendous advances have been accomplished during the recent years in the analysis of coupled problems for fluid flow with structural interactions. The basic capabilities of the analysis methods are presented in numerous papers by Bathe et al. [1–5] and fully implemented in the ADINA system [6,7]. These very powerful analysis methods must be applied and incorporated now into the engineering design process.

For a fin structure, see Fig. 1, subjected by subsonic and supersonic fluid flow the structural behaviour will be investigated now. The purpose of this investigation is to study the fluid–structure interaction of the fin profile structure and the fin structure spring support properties with respect to aeroelastic effects considering transient fluid flow conditions up to Ma 2.0 and for stationary fluid flow conditions at Ma 2.0.

The design of fin structures for use in subsonic and supersonic fluid flow draws on many multidisciplinary requirements between aerodynamic, structural mechanics, design and manufacturing knowledge.

All these demands should be considered in a multidisciplinary analysis. Usually, we start with classical aerodynamics which normally means that a rigid fin structure is assumed for test and analysis and the corresponding aerodynamic loads are derived for selected stationary flow conditions across the required aerodynamic design range. However, in real physical hardware the mechanical design envelope is limited due to aerodynamic performance and weight limitations, therefore the requirement for a rigid fin structure can be fulfilled approximately only. Design constraints are also given regarding size and shape for the actuator mechanism and therefore the stiffness of the actuator mechanism will be also limited. Additionally, the stiffness constants of the fin structure support can vary or change due to manufacturing tolerances and fatigue behaviour over the intended life cycle. The effect of nonlinearities as they might occur are certainly difficult to predict in the classical design process.

If possible, the interaction between all these influence parameters should be considered in a very early design phase. A fully coupled fluid–structure interaction analysis taking into account various stiffness parameters and fluid flow conditions will be performed using ADINA/ADINA-F [6,7].

Due to the complexity of this problem and to limit the computational effort, a two dimensional fin profile

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doi:10.1016/S0045-7949(02)00423-6

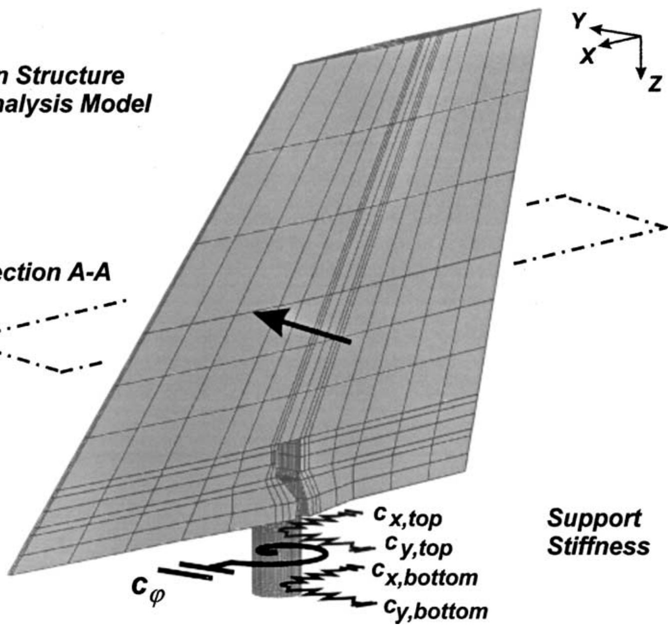

Fig. 1. Fin structure and boundary conditions (3D-model).

analysis model is derived from the three dimensional fin structure. The analysis cross-section A–A is defined at $\xi = 0.476$ of the fin span $s = 168.0$ [mm]. The stiffness properties for the support conditions of the two dimensional profile cross-section A–A can be obtained by a 3D-finite element static analysis.

2. Frequency analysis of fin profile (2D-analysis)

To perform a fin profile structure sensitivity analysis with respect to aeroelasticity a detailed frequency and mode shape analysis is necessary. The geometric properties for the two dimensional analysis are derived from the specified cross-section A–A, and the fin structure support is defined according to the hinge moment position. The extracted fin profile structural analysis model is shown in Fig. 2 and the corresponding geometric dimensions are given as $c_1 = 77$ [mm], $c_2 = 130$ [mm] and $c_3 = 22.4$ [mm].

The flexibility of the fin profile structure, a metal forging part, is defined by the bulk modulus of $E = 45,000$ [N/mm^2]. The mechanical properties given in Table 1, including the mass, center of gravity and moment of inertia, are calculated using the geometric properties of the cross-section A–A and the material density of $\rho = 1.74$ [kg/dm^3].

To evaluate the fluid–structure interaction behaviour of a rigid fin structure in comparison to a flexible fin structure and various support spring stiffness parameters

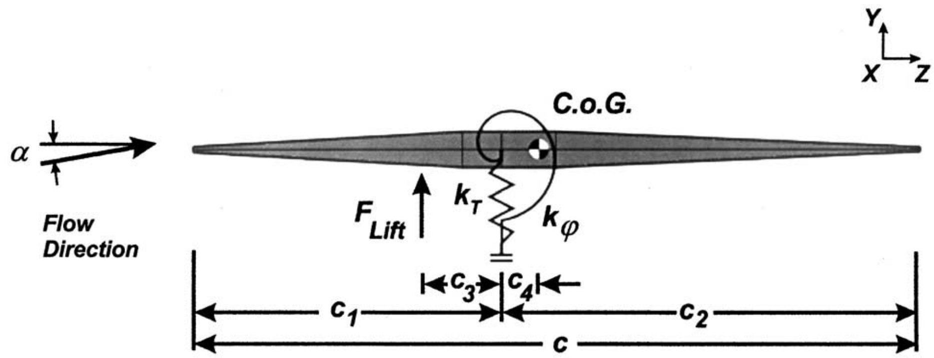

Fig. 2. Supersonic fin profile (2D-model).

Table 1
Mass properties of 2D-fin section model

Mass	$m = 0.388$ [kg]
C.o.G.	$y = 0.00000$ [m]
	$z = 0.02239$ [m]
Roll inertia	$I_{xx} = 0.8845\text{E–}03$ [kg m^2]
Pitch inertia	$I_{yy} = 1.7969\text{E–}03$ [kg m^2]
Yaw inertia	$I_{zz} = 0.9165\text{E–}03$ [kg m^2]

with different torque stiffness values, four different analysis cases are created and described in Table 2.

The intention of the specified stiffness cases is to start the investigation with a rigid fin structure profile and a large support stiffness, case A. Then in the following cases the fin structure becomes flexible and the torque stiffness of the spring support is reduced also. The transversal spring stiffness is kept constant, however it could be varied also according to any design requirements.

Before starting the numerical analysis the first and the second frequencies are calculated for case A to calibrate the finite element model. According to a classical single degree of freedom system, i.e. for translational motion $\omega = \sqrt{k/m}$, we obtain using the mass properties of Table 1 and stiffness properties of Table 2 the first frequency of $f_1 = 1051$ [Hz] for translational motion and the second frequency for torsional motion of $f_2 = 3296$ [Hz].

Of course, all specified analysis cases for the different stiffness variations can be easily calculated using ADINA [6] and are presented in Table 3. For case A we recognize a good agreement with the analytical solution, which can be considered as a calibration case for the further investigation.

In advance to the following fluid–structure analysis it makes sense to discuss the frequency analysis results. The mode shapes for analysis case A, presented in Fig. 3a, show the expected typical plunge and pitch motion

Table 2
Analysis case and fin support stiffness table

Analysis case	Fin structure support stiffness		Analysis case description
	Transversal stiffness [N/m]	Torsional stiffness [Nm/rad]	
Case A	17.0E+06	0.4E+06	Rigid fin structure
Case B	17.0E+06	0.4E+06	Flexible wing structure
Case C	17.0E+06	0.4E+05	Flexible wing structure
Case D	17.0E+06	0.2E+05	Flexible wing structure

Table 3
Fin profile frequencies, modal participation factors and mode shape description

Analysis cases and stiffness	Mode	Frequency [Hz]	Modal participation factor	Mode description
Case A	1	1049.0	1.5833	Plunge mode in y-direction
	2	3291.0	−0.7951	Pitch mode about x-axis
Case B	1	809.4	0.8127	Plunge mode + profile bending at trailing edge
	2	1237.0	1.1314	Pitch mode + profile bending at leading and trailing edge
	3	2131.0	1.3731	First bending mode of fin profile
	4	4355.0	1.2415	Second bending mode of fin profile
Case C	1	706.6	0.2963	Combined pitch and plunge mode + profile bending at trailing edge
	2	1016.0	1.1327	Combined pitch and plunge mode + profile bending at leading edge
	3	2033.0	1.3447	First bending mode of fin profile
	4	3936.0	−1.4165	Second bending mode of fin profile
Case D	1	597.8	−0.0099	Combined pitch and plunge mode + profile bending at trailing edge
	2	961.8	1.3544	Combined pitch and plunge mode + profile bending at leading edge
	3	2006.0	−1.3363	First bending mode of fin profile
	4	3825.0	1.4556	Second bending mode of fin profile

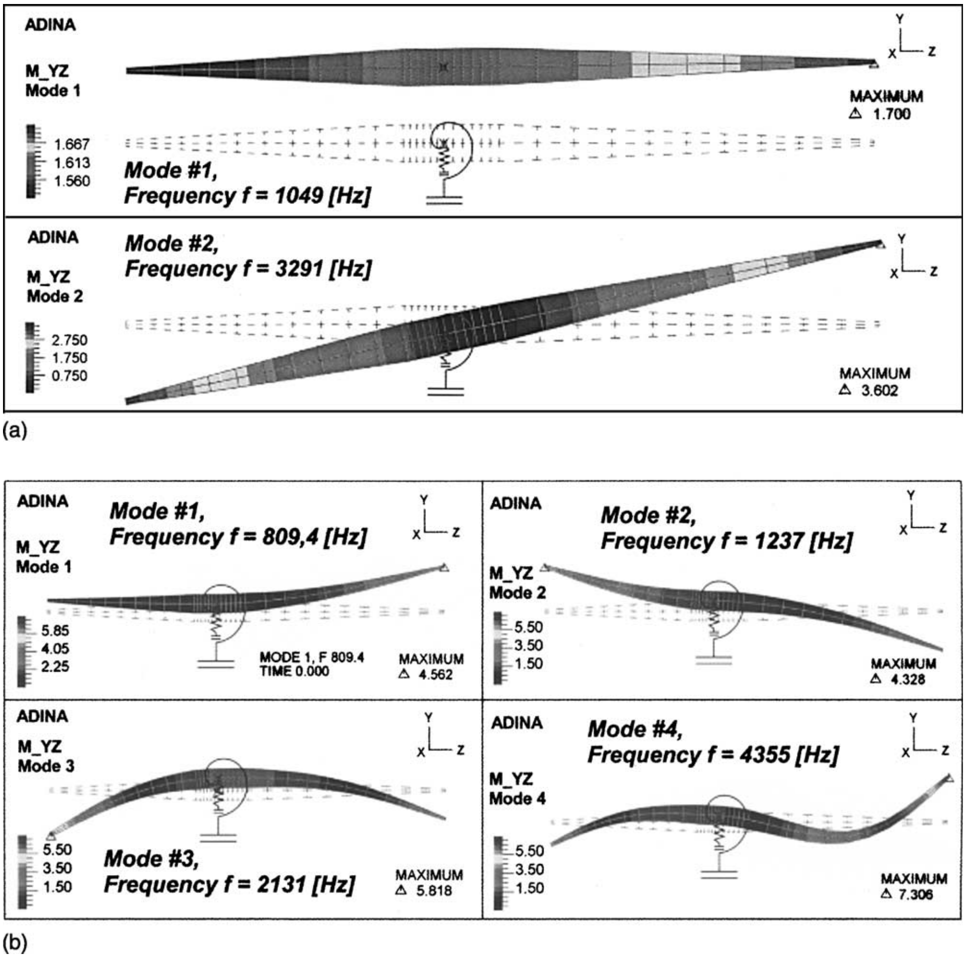

Fig. 3. (a) Frequency analysis—stiffness case A, mode shapes 1–2. (b) Frequency analysis—stiffness case B, mode shapes 1–4.

corresponding to the calculated frequencies. Including the fin structure profile flexibility, performed in analysis case B, the corresponding mode shapes, presented in Fig. 3b, show a significant difference compared to the response of analysis case A. The detailed description of the frequency and mode shape behaviour for all analysis cases is given in Table 3. Of course, differences may occur, but the fin structure profile flexibility reduces the frequency response significantly up to ~239.6 [Hz], and if we consider an excitation range up to 2000 [Hz] there may be expected that the total dynamic response due to aerodynamic pressure loading may affect more than one mode shape. The analysis cases C and D respond with decreasing frequency values compared to the previous analysis cases, but the mode shape behaviour does not change significantly. Considering the modal participation factors of all analysis cases, we can see that in analysis case A the translational motion dominates the frequency response whereas in analysis cases B, C and D the profile bending modes may be significant for the dynamic response. Finally, we also can state that the magnitudes for the frequency values are very high. This means that any dynamic response effects may enter very fast and/or may occur over very short time periods.

3. FSI analysis of fin profile (2D-analysis) due to an increasing Mach number flow

Reconsider a standard design process for our supersonic fin structure profile in which the aerodynamic forces and moments are calculated using classical aerodynamic theories based on rigid body aerodynamics, computational fluid dynamics (CFD) computations or on wind tunnel measurement results. A common assumption in all these methods is that the structure will not change its shape and its position, that is the structure will not respond. Of course, in a wind tunnel experiment the structure can be deformed or destroyed but normally this is not intended, except in flutter experiments. Also, the wind tunnel experiments provide for accurate measurements considering steady state conditions of Mach number, angle of attack (AOA) and side slip angle. Hence proceeding in that way, we obtain values to predefined aerodynamic conditions only. Results must be sequentially evaluated and optimized by an multidisciplinary iteration process between aerodynamics and structural mechanics.

Performing now a fluid–structure interaction analysis using CFD and finite element methods we also have to approximate some uncertainties which does not allow to predict the exact physical flow conditions around the structure. The main influence quantities are the boundary layer profile and the structural response behaviour. Both of these effects may be highly nonlinear and time dependent. The boundary layer profile will be a function of structure geometry, fluid properties, profile roughness of the structure surface and, in high Mach number flow, of aerodynamic heating effects. The structural response, as profile movement and deformation, will be mainly a function of aerodynamic pressure distribution in dependency of free stream velocity combined with shock and expansion wave effects. Hence, the structural behaviour at time $t + \Delta t$ in an increasing fluid flow will be always a function of the flow situation and structural behaviour at time t and must be obtained by an incremental solution process for the fluid and the structure, fully coupled to each other.

To solve in this work for the structural behaviour of the fin profile structure over a certain functional range, the flow velocity will be increased up to Ma 2.0 in a defined time domain of $\Delta t_R = 1.0$ [s]. This means that an unsteady transient dynamic analysis will be performed to analyse the structural response over the specified time range and to evaluate the aeroelastic behaviour of the mechanical system. The analysis is performed using the program system ADINA/ADINA-F [6,7]. To describe the structural behaviour, large deformations are assumed and no structural damping is specified. The fluid properties are specified using standard atmospheric conditions and the AOA is chosen to be $\alpha_0 = 5.0$ [deg]. To characterize the fluid behaviour we can use the Reynolds number using Eq. (1)

$$Re = \frac{v_\infty l_{\mathrm{ref}}}{\nu} \tag{1}$$

where v_∞ defines the free stream velocity, l_{ref} the reference length of the structure and ν is the kinematic viscosity of the fluid. Calculating the Reynolds number for the maximum defined fluid velocity Ma 2.0 using Eq. (1) we obtain $Re_{\mathrm{Ma\ 2.0}} = 78.66 \times 10^5$. According Schlichting/Truckenbrodt [8] we can expect for the prescribed fluid velocity range of Ma 2.0 a Reynolds number $Re \gg 1.1 \times 10^5$ where the boundary layer becomes turbulent. Therefore, summarizing, for all flow conditions the compressible fluid flow Navier–Stokes equations are

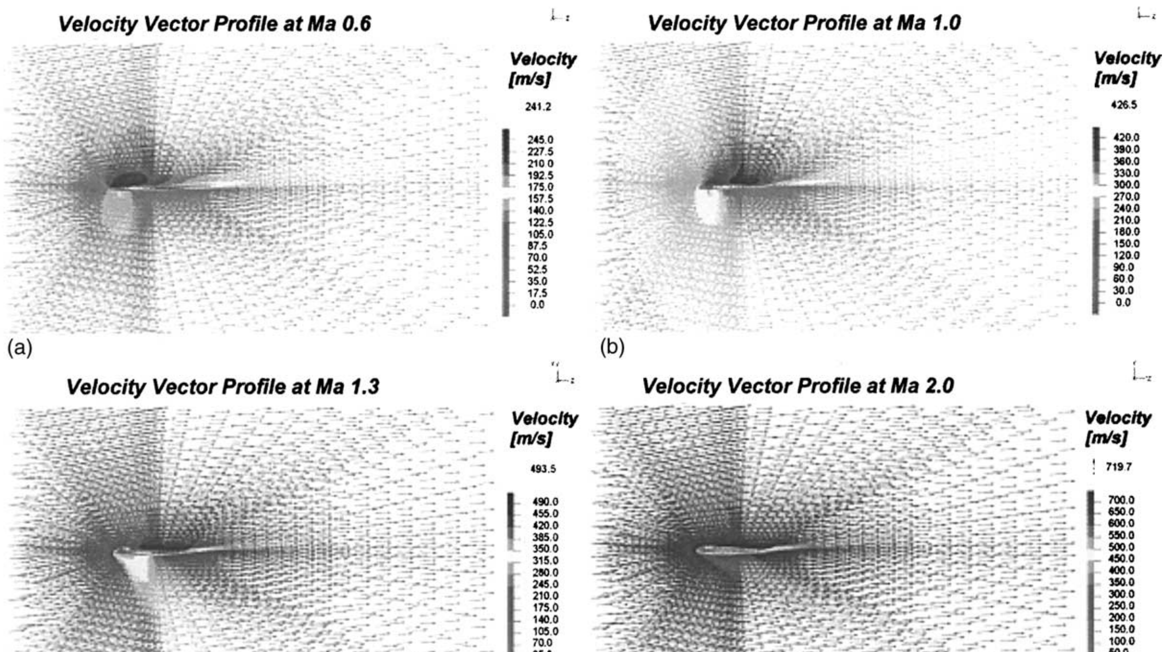

Fig. 4. (a–d) Velocity vector profiles up to Ma 2.0.

solved incrementally up to Ma 2.0 and to model the turbulence behaviour in the boundary layers, the k/ε-model is used. The interface conditions between the fluid and the structure are solved iteratively by an automatic iteration procedure in the ADINA System [6,7] for each timestep, respectively, for each free stream velocity up to Ma 2.0.

To show results of the solution the fluid velocity vector profiles, see Fig. 4a–d, and the aerodynamic pressure profile, see Fig. 5a–d, of various time steps as a function of Mach number are presented. All the fluid quantities, i.e. aerodynamic pressure in Fig. 5, are calculated on the deformed and moving fin structure profile. The time history of aerodynamic pressure profiles show also subsonic and supersonic flow field characteristics including shock and expansion wave effects.

For aerodynamic and structural design we are mainly interested in the forces and moments at the spring support. These quantities are directly obtained from the analysis as a function of Mach number. The aeroelastic response of the translational force, the torque moment and the drag force are plotted for different analysis cases in Fig. 6a–c. As an additional reference, the results of analysis cases A, B and C are related to those of a rigid fin profile with rigid support conditions. We recognize that the influence of the fin structure flexibility and the selected support stiffness values is negligible for the translational spring force F_T and the drag force F_D response. There are some small and short disturbances entering the transonic region only. However, deviations in spring moment M_H response for specific situations can be observed. Up to a free stream velocity up to ~Ma 0.87 the spring moment response, is from an engineering point of view, identical in all analysis cases. Above this free stream Mach number there is a significant difference between the spring moment response of the rigid fin structure profile and the flexible fin structure profile. Differences between the rigid fin structure and the rigid fin structure profile on the elastic support, case A, are negligible as also the differences between analysis cases B and C. We recognize that the total spring moment response behaviour differs from the beginning of transonic region up to supersonic fluid flow. This would mean that the spring moment seems to be a function of the moving aerodynamic lift point based on different flow regimes and the fin profile structure flexibility. For a better understanding of the spring moment response the deformed fin structure profile history for selected free stream Mach numbers of analysis case A and analysis case C can be compared. If we consider the fin profile movement and deformation response of analysis case A, the fin profile suffers an offset in y-direction up to Ma 2.0 only, see Fig. 7. So we can assume that the flexibility is dominated by the translational spring stiffness and the corresponding flow field conditions may be very close to a rigid fin structure. In analysis case B the fin structure profile deformation occurs according the aerodynamic lift point movement and aerodynamic pressure distribution as a function of free stream Mach number. This means in subsonic fluid flow the leading edge of the fin structure profile will deform significantly and in supersonic fluid flow the trailing edge will be deformed mainly, see Fig. 8. Of course, the fin profile bending

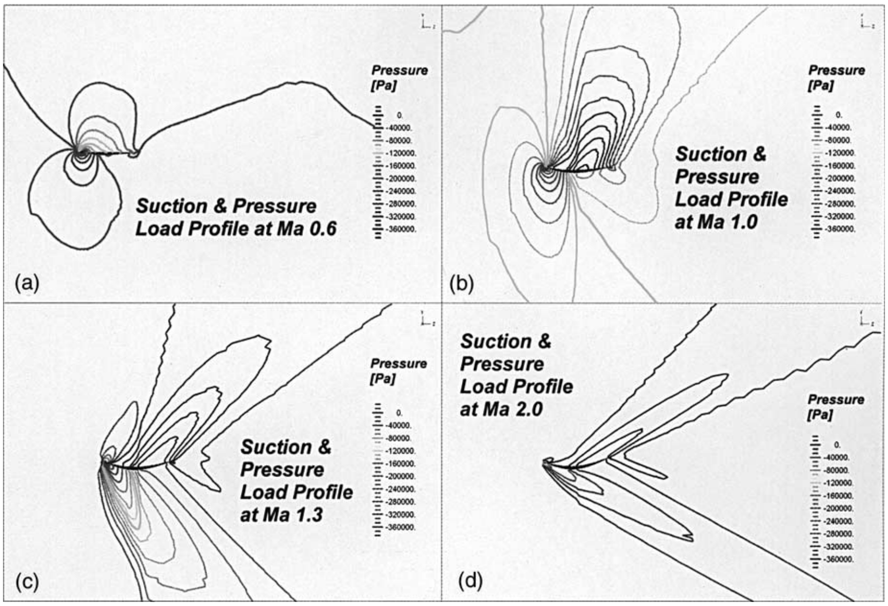

Fig. 5. (a–d) Suction and pressure load profiles on deformed fin profile structure up to Ma 2.0.

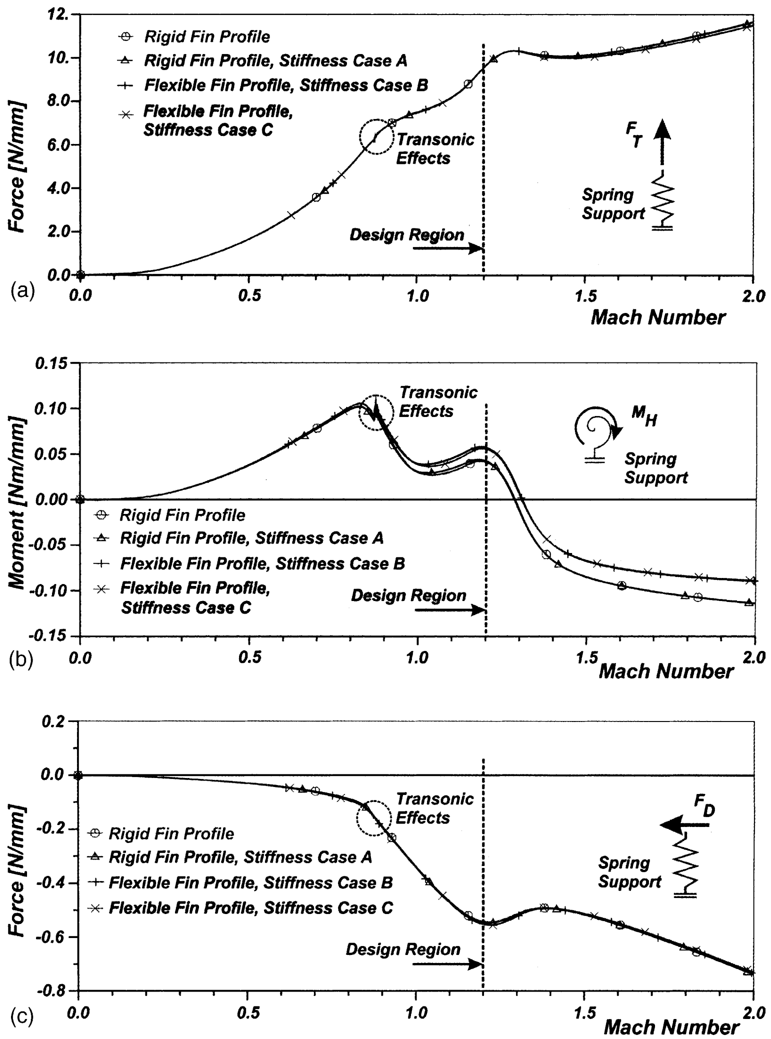

Fig. 6. (a) Translational spring force history due to unsteady aerodynamic pressure load, (b) spring moment history due to unsteady aerodynamic pressure load and (c) drag force history due to unsteady aerodynamic pressure load.

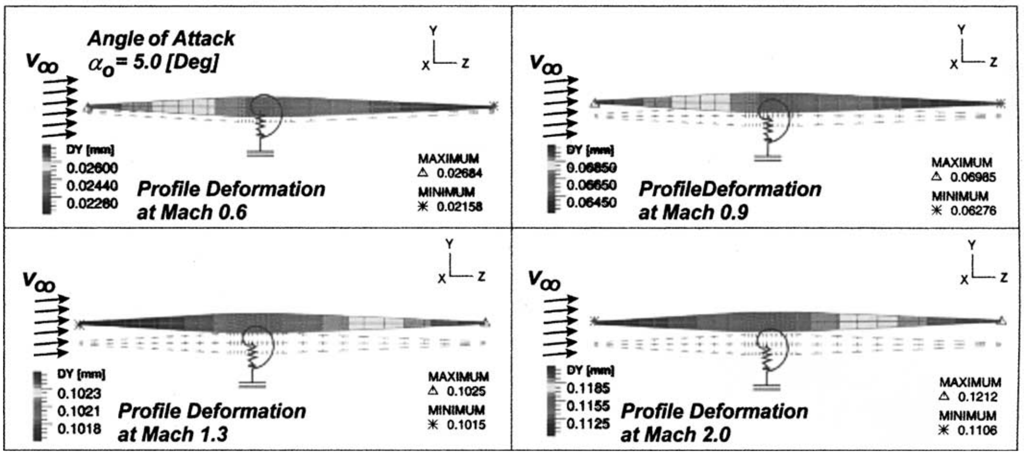

Fig. 7. Fin profile deformation, stiffness case A.

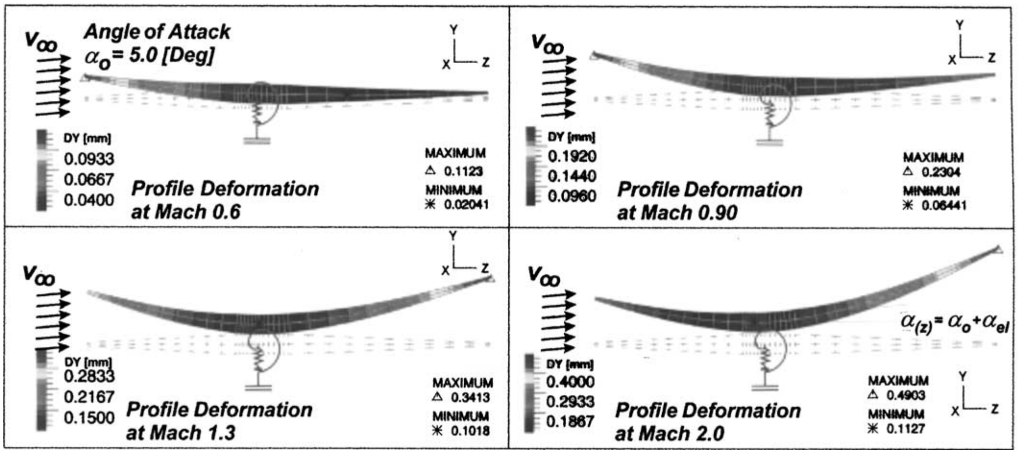

Fig. 8. Fin profile deformation, stiffness case C.

deformation in this analysis case is also superimposed by a translational fin structure profile offset. From a structural mechanics point of view the total amount of profile movement and deformation is very small. The effective angle of attack for the free stream Mach number related to the whole profile length including profile elasticity is calculated approximately as $\alpha_{\text{eff}} = \alpha_0 + \alpha_{\text{el}} = 5.0 + \sim 0.1 \approx 5.1$ [deg]. However, in relation to the boundary layer thickness the calculated deformations are relatively large.

4. FSI analysis of fin profile (2D-analysis) at steady-state flow conditions of Mach 2.0

In the previous investigation we analyzed the fin behaviour over a range of Mach number, up to Ma 2.0, when this flow condition is reached over a specific time range. The global aerodynamic and structural behaviour were calculated for the fin profile. For detail mechanical design process the structural response at a stationary Mach number flow will, however, be of more interest. Therefore, next, the fin structure profile will be subjected to a constant Mach number flow of Ma 2.0 and the response due to different analysis cases will be calculated, similar as in the previous section. The flow field conditions are identical to before and the AOA is $\alpha_0 = 5.0$ [deg].

The stationary flow field characteristics for this purpose are calculated also by a nonlinear transient fluid–structure interaction analysis but in this case steady state conditions are established for initial conditions according to CFL criteria. This is required to reach the corresponding initial structural deformation for the predicted free steam conditions. To investigate basic effects the calculation for analysis case C will be discussed now. The fluid–structure analysis using ADINA/ADINA-F [6,7] is performed in the time domain until the response process shows a stationary condition. After a short period of initial oscillations, a stationary harmonic motion of the fin structure profile is reached and the profile structure performs limit cycle oscillations (LCO). If we focus now on the structural movement, deformation and stresses we recognize a maximum displacement amplitude up to $u_y \approx 1,2$ [mm], see Fig. 9. The corresponding stresses in the fin structure profile can be also extracted and a classical bending behaviour near the spring support can be recognized at the deformed fin profile structure. Evaluating the normal stress σ_{zz} we obtain $\sigma_t \approx 42.5$ [N/mm^2] for tension and $\sigma_c \approx -42.7$ [N/mm^2] for compression.

To present the fin profile motion a set of evaluation points, named A–E, is defined along the profile length, where point B and point D are representative for the profile quarter points, see Fig. 10. In the displacement history at the profile points we only recognize a significant motion for the profile points A, D and E. The phase offset between the response curve of point A and point E in combination with a small oscillation of point C allows the conclusion that a combined pitch and plunge motion according to the previous described mode shape behaviour happens. Finally we consider the time history of the support spring moment M_H in Fig. 11 for various analysis cases. If we compare the spring moment response over time a harmonic response can be observed for all analysis cases. The mean value of the steady state moment response for all analysis cases is in a magnitude of $M_H \approx -0.13$ [Nm/mm] what is approximately identically and comparable with the response value in Fig. 6b at Ma 2.0, but due to steady state flow conditions this value oscillates with various high amplitudes for the different analysis cases about the mean value. More than

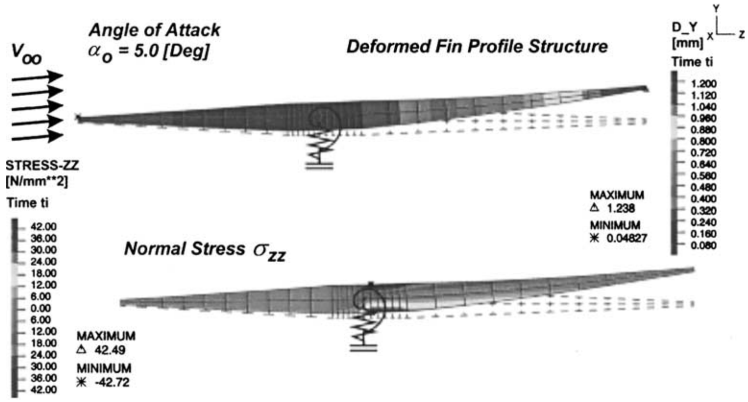

Fig. 9. Fin profile deformation and normal stresses at time t_i due to flow conditions at Ma 2.0.

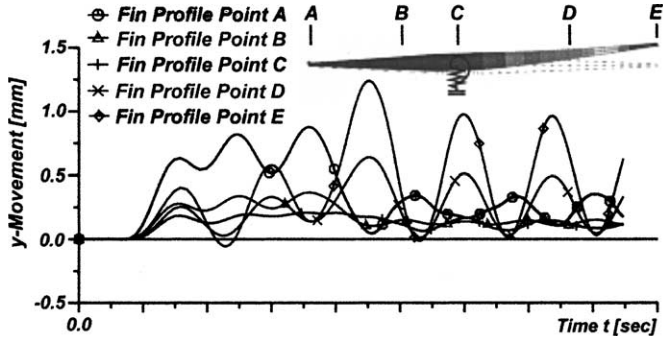

Fig. 10. Time history of fin profile structure movement due to flow conditions at Ma 2.0.

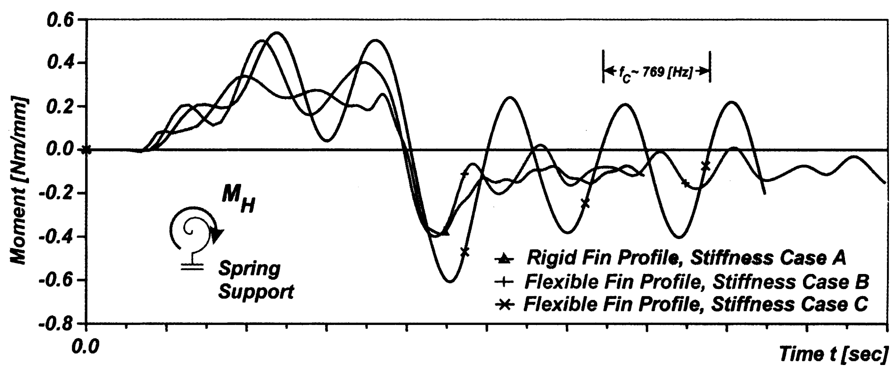

Fig. 11. Time history of spring moment due flow condition at Ma 2.0.

one frequencies seems to be part of the total spring moment response in analysis cases A and B, where the response in analysis case C is dominated by a single frequency and a very high amplitude. The response amplitudes of spring moment M_H including the corresponding frequency of $f_c \approx 769$ [Hz] must be considered in mechanical design with respect to fatigue.

5. Conclusion

Summarizing the previous investigations it can be stated that a wide range of aerodynamic and structural mechanics effects can be analysed using the fluid–structure interaction capability of ADINA/ADINA-F [6,7]. These capabilities were applied to a two dimensional rigid and flexible fin structure profile including various support stiffness cases subjected to subsonic and supersonic fluid flow.

The fin profile structure was subjected to an increasing free stream Mach number up to Ma 2.0 in a specified time range and no aeroelastic instability effects occurred. It was shown that the flexibility influence of the fin profile structure may be negligible at cross-section A–A for the translatoric force and the profile drag force at the profile support, but it cannot be neglected for the torque moment response. This means that the sensitivity of torque moment behaviour as a function of structure flexibility must be considered in detail in high Mach number flow.

For stationary Mach number flow at free stream conditions of Ma 2.0 the structural response of the fin profile was calculated. The analysis has shown that the fin profile structure does not remain in a steady state position and a harmonic fin profile motion occurs. As a function of profile stiffness, LCO for the spring moment response, respectively the hinge moment, with high amplitudes may be expected due to high Mach number flow.

Of course, more detailed investigations must be performed for different AOAs and Mach numbers in a complete design process but the investigation has shown that very valuable results for complicated fluid–structure interaction problems can be obtained using the FSI capability of ADINA/ADINA-F.

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