Experimental investigation of the unsteady behavior of a compressor cascade in an annular ring channel

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Abstract

A compressor cascade has been experimentally investigated in an annular non-rotating test facility with regards to its steady-state and time dependent aerodynamic characteristics. The cascade consisted of 20 blades with a NACA 3506 profile form. The blades were vibrated in the first bending mode at a frequency of about 225 Hz. The interblade phase angles and the amplitude of the blade vibration were controlled independently with a magnetic excitation and control system. Several blades were equipped with steady-state pressure taps and piezoelectric pressure transducers. Upstream and downstream probe traverses were used to check the steady-state flow conditions.

Tests were done to validate the superposition principle at nominal flow conditions, for a high incidence angle and a high Mach number case. For this, the cascade was excited in both the single blade vibration mode and the traveling wave mode. The unsteady response for different vibration amplitudes for the nominal flow conditions was examined. Also, error margins of the steady-state Mach numbers and the time dependent pressure coefficients were estimated.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>Blade chord length</td>
<td>[m]</td>
</tr>
<tr>
<td>(\tilde{c}_p(x,t))</td>
<td>Unsteady perturbation pressure coefficient: (\tilde{c}<em>p(x,t) = \frac{1}{h} \cdot \frac{\hat{p}(x,t)}{p</em>{w1} - p_1})</td>
<td>[-]</td>
</tr>
<tr>
<td>(\tilde{c})</td>
<td>Quasi-steady perturbation pressure coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>f</td>
<td>Blade vibration frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>h</td>
<td>Dimensionless (with chord) bending vibration amplitude</td>
<td>[-]</td>
</tr>
<tr>
<td>(\hat{L})</td>
<td>Blade vibration influence coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>k</td>
<td>Reduced frequency: (k = \frac{\omega \cdot c}{2 \cdot u_2})</td>
<td>[-]</td>
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In the course of the last few years turbomachinery blading has become longer and more slender. At the same time the loading has increased. As a result, the blades have become more susceptible to mechanical and aerodynamic excitation. In some cases the aerodynamic excitation and the induced blade vibration have led to the failure of the blading or even to the destruction of the whole machine. Conditions under which vibrating blades produce aerodynamic forces that further increase the vibration are especially dangerous. For this reason one is interested in gaining more knowledge about the circumstances under which self-
excited blade vibrations may appear. Experiments in test facilities increase the physical understanding and serve as a data base for the calibration and development of unsteady numerical codes to predict potentially dangerous flow conditions (e.g. it was found that the unsteady influence of shocks and separation bubbles can be of considerable importance for the overall damping of a cascade).

This paper presents tests with a vibrating compressor cascade in the annular test facility of the Laboratoire de thermique appliquee et de turbomachines (LTT). It discusses aspects of the quality of the unsteady measurements and presents test data to validate the superposition principle for a few chosen flow cases for the compressor cascade. The superposition principle is important for experiments as well as for calculations of vibrating blade rows. It states that it is possible to obtain the unsteady pressures in a vibrating cascade by linearly summing up the influences of the individually vibrating blades. One is interested to know if and where there exist limits of the validity of this superposition principle.

**Test facility and cascade geometry**

The tests on the vibrating cascade were performed in the non-rotating annular cascade tunnel at the Swiss Federal Institute of Technology, Lausanne [Bólcs, 1983]. The flow angle in the test section can be regulated from axial (0°) to ± 75°, and the inlet Mach number can be varied from 0.3 to 1.6. The flow conditions are measured with aerodynamic probes and pressure taps. Schlieren optics and laser holography can be used for optical flow measurements and visualization (Fig.1).

For time-dependent measurements the blades in the test cascade are mounted on elastic springs and are driven into a vibration mode by means of a vibration control system [Kirschner et al., 1980] (Fig. 2). Each blade is elastically suspended on a spring-mass system, designed to produce the desired eigenfrequencies, as well as the vibration direction of the first bending mode. The blades are forced into vibration by means of individual electromagnetic exciters, each with its own feedback loop. Thus, phase and amplitude can be chosen individually for each blade. The
parameters of the cascade can be found in Tab. 1. At the present four blades are furnished with pressure taps and two blades are equipped with piezoelectric pressure transducers (ENDEVCO 8515-50A and ENDEVCO 8514-50A). It is planned to put more transducers onto the blades for a more detailed study of the overall damping behaviour of the cascade in the future. The transducers were calibrated for fluctuating pressures and for acceleration forces.

### Evaluation and analysis of the time dependent test data

Two methods are used for the evaluation of time dependent test data at the LTT. It can be shown that for the damping behavior of a vibrating blade only the unsteady pressure components with the same frequency as the blade vibration are important. The total energy input into the blade of the fluctuating pressure components with frequencies other than the blade frequency results to zero over time [Schläfli, D.; 1989; Széchényi, E.; Girault, J. P.; 1983]. The first method is based upon the cross correlation of the pressure signals with the vibration blade signal [Schläfli, D.; 1989] and the second method is based upon an ensemble averaging technique. It was found that the results of both methods match almost perfectly. In the following, the ensemble averaging technique is briefly described.

The unsteady tests with the vibrating cascade are done in a controlled vibration mode. The frequency, the amplitude and the phase relation between the blades are kept...
constant over time. Thus, the blade vibration can serve as a well known and well defined reference signal and the time dependent pressures can be regarded as the response to this reference signal. The time dependent signals are digitized and stored on-line in computer memory. One obtains the exact time of each sampled data point from the known sampling rate of the digitization. All data points are now projected into one period $T_0$ of the reference signal (Fig. 3). An averaged signal can be calculated from the resulting set of points (Fig. 4). This averaged signal is the unsteady pressure response to the blade vibration at the blade vibration frequency. An FFT is used to determine the exact amplitudes and phase shifts of the averaged signals. The higher harmonics in the signals are also obtained. Then, the signals are corrected for damping and phase shifts in the measuring chain and for the acceleration sensitivity of the piezoelectric pressure transducers and they are converted to unsteady pressure coefficients. The spread of the samples around the averaged signal is statistically analyzed to estimate a confidence interval of the calculated unsteady pressure amplitude and phase shifts.

The time dependent data are analyzed with the influence coefficient technique [Bölcs, A; Fransson, T. H.; Schläfli, D.; 1989; Fransson, T. H.; 1990]. The influence coefficient technique is based upon the superposition principle which states that the observed time dependent pressures at any given point $x_i$ (e.g. a pressure transducer position on a blade surface) in a vibrating cascade are equal to the linear superposition of the pressure waves that are produced by each vibrating blade $k$ and that propagate into the flow field (eq. [1]). The unsteady pressure that is caused by a blade $k$ on point $x_i$ depends on the amplitude $q_k$ and the phase $\phi_k$ of the blade vibration (eq. [2]) and of the influence coefficient $L_{i,k}$ (eq.[3]). The influence coefficient has a phase shift $\Omega_{ik}$ referenced to point $x_i$. The reference phase usually is chosen to be the phase of the vibration of the blade upon which point $x_i$ is situated. The influence of a vibrating blade upon a point situated on its surface is called the eigeninfluence. From a set of different vibration modes of the vibrating blades the influence coefficients are obtained experimentally. For example: to obtain the influence coefficients of eight vibrating blades for a point $x_i$ it is necessary to measure the unsteady pressures $\tilde{c}_p(x_i,t)$ for at least eight
different vibration modes and to solve the resulting complex system of equations (eq. [1]). If the unsteady pressures at \( x_i \) really are a linear superposition of the influences of all vibrating blades, then it should not matter what vibration modes are chosen. Any set of travelling wave modes (constant amplitude \( \tilde{q} \) and constant interblade phase angle \( \sigma \)) of eight different interblade phase angles could be chosen or each blade could be vibrated one after the other (single blade vibration mode). The solutions should be the same. But, in the case that the superposition is nonlinear, then different solutions would be obtained for different sets of vibration modes.

\[
\tilde{C}_p(x_i, t) = \sum_{k=1}^{N} \tilde{q}_k(t) \cdot \tilde{L}_{i,k} \quad [1]
\]

\[
\tilde{q}_k(t) = \tilde{q}_k \cdot e^{j(\omega t + \phi_k)} \quad [2]
\]

\[
\tilde{L}_{i,k} = \tilde{L}_{i,k} \cdot e^{j\Omega_{i,k}} \quad [3]
\]

A convenient way to show the unsteady pressure coefficients at a point \( x_i \) for a range of interblade phase angles is the use of a phase diagram in the complex plane. As the unsteady pressure coefficients have a magnitude \( |\tilde{C}_p(x_i)| \) and a phase shift \( \phi(x_i) \) they can be represented as a vector in the complex plane with \( \tilde{C}_p(x_i) = [|\tilde{C}_p(x_i)| \cdot \cos(\phi(x_i)) ; |\tilde{C}_p(x_i)| \cdot \sin(\phi(x_i))] \). In the case of a cascade vibrating in travelling wave mode, each different interblade phase angle \( \sigma \) results in a different vector of \( \tilde{C}_p(x_i, \sigma) \) in the complex plane. The end points can be connected for the interblade phase angles from 0° to 360° and one obtains a closed curve - the phase diagram of the unsteady pressures at \( x_i \). As mentioned above, the unsteady pressures for a travelling wave mode can also be reconstructed from the influence coefficients (Fig. 5). Thus, phase diagrams of unsteady pressures obtained from travelling wave mode experiments can be compared to reconstructed phase diagrams that are calculated from the influence coefficients of any vibration mode. It is also possible to reconstruct and compare the influences of certain blades at a point \( x_i \) while leaving out other blades.

**Data spread of the steady state and time dependent test data**

To compare test data that was taken for different test conditions as well as for the analysis of unsteady influence coefficients and the comparison of experimental and test data, it is important to have an estimate of the error margins and of the spread of the experimental data. This is especially important for the unsteady test data as the time dependent pressures are often very small compared to the noise levels on those signals.

A test series was performed to estimate the steady state and time dependent repetivity and periodicity of the experimental data. The annular test facility was rotated in the circumferential direction in steps of 18° (which is the spacing of the blades). Time dependent and steady-state measurements were taken with the instrumented blades being positioned in different circumferential channel locations. This served to examine the periodicity of the test data in the test facility. The repetivity was checked with repeated measurements in the same channel position. The flow conditions in the test facility were kept constant. The inlet and
outlet flow conditions could only be measured at one cascade position since the stream probes are fixed and can not be rotated with the cascade [Bölcs, A.; Körbächer, H.; 1993].

It was found that the steady-state repetivity of the blade surface Mach numbers is in general good. Repeated measurement at the same circumferential channel position gave identical results. The same results are also found for different blades with pressure taps at the same chordwise positions (e.g. Fig. 6). The periodicity on the other hand is not quite as good as the repetivity. It was found that the periodicity is not good in a region between -72° and -18° circumferential channel position and there especially for pressure taps close to the leading edge (Fig. 6, x/c=0.14). However, even there the repetivity is excellent.

This region was identified as the position in the test facility where the probe holders are situated upstream of the cascade. The periodicity is much better elsewhere. It was concluded that steady state measurements can be done with a high repetivity and that the periodicity in the channel is good except there where probes disturb the upstream flow. The leading edge region is particular sensitive to those disturbances.

The unsteady repetivity and periodicity were also checked. Eighteen tests in six different circumferential channel positions were performed at the same flow conditions. The average amplitudes and phase angles were obtained from all 18 tests. The mean deviations from those measurements are given in Table 2.

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**Fig. 6:** Repetivity and periodicity on suction surface for two pressure tap locations 
(M₁= 0.887, β₁= 49°, i₁ = 2.3°)

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**Tab. 2:** Comparison of data spread and error intervals (time dependent pressure amplitudes and phase angles) (M₁= 0.887, β₁= 49°, i₁ = 2.3°, σ = 180°)

<table>
<thead>
<tr>
<th>x/c [-]:</th>
<th>Amp.</th>
<th>Phase</th>
<th>Repetivity (measured)</th>
<th>Periodicity (measured)</th>
<th>Evaluation (estimated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>mean dev. Δp [%]</td>
<td>mean dev. Δφ [°]</td>
<td>mean dev. Δp [%]</td>
</tr>
<tr>
<td>PS01</td>
<td>0.084</td>
<td>27.66</td>
<td>-47.7</td>
<td>1.07</td>
<td>0.39</td>
</tr>
<tr>
<td>PS02</td>
<td>0.232</td>
<td>10.89</td>
<td>-26.4</td>
<td>0.91</td>
<td>0.43</td>
</tr>
<tr>
<td>PS03</td>
<td>0.384</td>
<td>4.01</td>
<td>-38.3</td>
<td>2.88</td>
<td>1.07</td>
</tr>
<tr>
<td>PS04</td>
<td>0.71</td>
<td>3.11</td>
<td>-182.1</td>
<td>1.62</td>
<td>0.89</td>
</tr>
<tr>
<td>SS01</td>
<td>0.09</td>
<td>12.01</td>
<td>97.9</td>
<td>1.29</td>
<td>0.47</td>
</tr>
<tr>
<td>SS02</td>
<td>0.194</td>
<td>9.59</td>
<td>120.3</td>
<td>2.65</td>
<td>1.07</td>
</tr>
<tr>
<td>SS03</td>
<td>0.297</td>
<td>8.60</td>
<td>138.7</td>
<td>1.57</td>
<td>0.93</td>
</tr>
<tr>
<td>SS04</td>
<td>0.4</td>
<td>9.29</td>
<td>137.8</td>
<td>0.78</td>
<td>0.47</td>
</tr>
<tr>
<td>SS05</td>
<td>0.71</td>
<td>14.63</td>
<td>145.0</td>
<td>2.33</td>
<td>0.68</td>
</tr>
</tbody>
</table>

1.68% 0.71° 13.9% 3.62° 2.36% 1.35°
averaged values for the periodicity spread were calculated. The mean deviations for the repetivity spread are calculated from an average value in each circumferential channel position. It was found that the measurements were highly repetitive. The mean deviation from an average value is in general less than 3% in amplitude and less than 2° in phase. This data spread lies well within the 95%-confidence intervals that were calculated from the spread of the sample points around the averaged pressure signals (Fig. 4). This shows that the statistical evaluation gives a good estimate of the probable data spread for repeated measurements in one channel position. Thus, it can be judged if differences between measurements are significant or whether they are just attributed to data spread when comparing test results.

Unfortunately the periodicity check was done with the instrumented blades placed between -90° and 0° circumferential channel position. This is the region where some steady state non-periodicity was found. This also shows up in the unsteady periodicity (Tab. 2). The mean deviations from the overall average values reach up to 25% for the time dependent pressure amplitude and 7° for phase angle with single maximum deviations of over 50% and 18° phase angle. It seems that the unsteady pressures are much more sensitive to a disturbance than the steady state Mach number distribution. However, the measurements of the time dependent pressures of the following tests were done with the instrumented blades being situated in a region with a good steady state periodicity.

In addition to the data spread due to of electric noise or aerodynamic turbulence, there may also be systematic errors like imprecise amplification factors, sensitivity shift of the transducers with temperature or inexact correction factors for damping and phase shifts. From our experience those errors can be considered as small. A more important error source is the acceleration sensitivity of the pressure transducers. This sensitivity results in an acceleration signal component that overlays the pressure signal. It depends on the frequency and the vibration amplitude. At 225 Hz and 0.4 mm vibration amplitude this may result in an acceleration signal of 1-2 mbar. The acceleration sensitivity is compensated in the evaluation process, but still a residual error of about 0.1-0.2 mbar with an unpredictable phase remains. This error is important for small signals.

Another source of data spread is the limited resolution of the digitization-card (Burr-Brown PCI 20023 M1). The card had a pressure resolution of 0.03 mbar for the presented tests. This effects only very small signals. For example: the mean deviation for the repetivity of PS04 in Tab. 2 is 1.68% at an average unsteady pressure amplitude of 3.11 mbar. This results in a spread of 0.05 mbar which is only slightly higher than the resolution of the card.

Fig. 7: Steady-state Mach number distribution on blade-surface at midspan (M₁ = 0.887, β₁ = 49°, i₁ = 2.3°)
Validation of the superposition principle

Steady-state test conditions

The repetivity check as well as the time dependent measurements to validate the superposition principle for the examined compressor cascade were done at a relatively high subsonic inlet Mach number ($M_{1s} = 0.887$). The incidence angle was low ($i_1 = 2.3^\circ$). Probe traverses with an L-probe approximately 60 mm upstream of the cascade showed that a uniform inlet flow field between 20% and 80% channel height is obtained. The Mach number distribution on the blade was taken at mid-span (Fig. 7). The first half of the suction surface is supersonic as can be seen. The Mach number distribution on the suction surface from x/c~0.3 down to the trailing edge is rather flat. This is attributed to a corner stall at the inner wall. Calculations with a three dimensional flow solver showed that the size of the corner stall depends a lot on the form of the inlet boundary layer. The test facility was not equipped to measure the boundary layer close to the walls. With small inlet boundary layers the code gave a small corner stall with strong shocks on the suction surface while with increased boundary layers the code showed a bigger corner stall with no shocks in the Mach number distribution on the surface as in the test.

Unsteady experiments at two other flow conditions will be also presented. One was taken at a lower inlet Mach number ($M_{1s}=0.791$) but at an high incidence angle ($i_1=11.4^\circ$). A paint flow visualization was done for this case. No separation was found at the leading edge. Indications of the corner stall were seen from x/c~0.4 downstream. At the trailing edge the traces of the corner stall extended from the inner wall up to the midspan of the blade. The Mach number distribution on the blade surface at midspan is seen in Fig. 8. The other test was done
at a high subsonic Mach number \( M_{1s} = 0.945 \) with an incidence angle of 4.7°. From the Mach number distribution (Fig.9) it can be seen that a shock was present on the suction surface at \( x/c \sim 0.2 \).

**Time dependent results**

Unsteady measurements were done in the traveling wave vibration mode and in the single blade vibration mode. However, only eight blades were vibrated in the traveling wave mode. All other blades were blocked. The movement of the non-blocked blades was recorded together with the pressure transducer signals. This way, the exact state of movement of all 20 blades was known at any given time, and it was known that no other blades except the unblocked blades could have an influence on the unsteady pressure distribution. In the travelling wave mode time dependent measurements were done at ten interblade phase angles ranging from 0° to 324° in steps of 36°. This yields a system of ten complex equations to calculate the influence coefficients for eight blades. As the system is overspecified, the solution was fitted to have the least quadratic error. In the single blade vibration mode each of the eight unblocked blades was excited in turn while the rest of the blades vibrated with small random movements. An exact solution is obtained for the influence coefficients of the eight blades with the eight resulting complex equations.

In Fig. A1 a) it is shown that the reconstruction of the unsteady pressures (at \( x/c = 0.232 \) on the pressure surface and \( x/c = 0.194 \) on the suction surface) based on the influence coefficients of the traveling wave mode fits in general very closely the measured data. Hence, the influence coefficients are an almost exact representation of the measured data. At this flow condition unsteady measurements were done at three different vibration amplitudes (\( A = 0.13\text{mm}; A = 0.28\text{mm} \) and \( A = 0.44\text{mm} \)) at ten interblade phase angles each in order to find out whether the unsteady pressure coefficients (and thus the influence coefficients) depend upon the vibration amplitude. If the coefficients depend upon the vibration amplitude it would mean that the propagation and superposition of the pressure waves can not be treated linearly for this case. But, in general the results at the three amplitudes agree very well (see Fig. A2 a)). Only at the leading edge was found a deviation that seems to be slightly higher than what could be explained from the possible data spread (Fig. A1 b)).

A comparison of the reconstructed phase diagrams of a travelling wave case and that of a single vibration case shows that the agreement is good (Fig. A2 b)). Deviations that are somewhat bigger than the expected measurement uncertainty can be found close to the leading edge and on the suction surface closer to the trailing edge (Fig. A3 a) and b)). If one compares the summed influences of the blades that contribute most to the unsteady pressures except the eigeninfluence (for the pressure surface those are the blades on the negative side \([m-1,m-2 \ldots]\) and for the suction surface those on the positive side \([m+1,m+2 \ldots]\)) then it can be seen that close to the leading edge on both surfaces the travelling wave mode shows a slightly higher influence of those blades than the single blade vibration mode (Fig. A4 a) and A5 a)). However, the phase angles fit very well. At other measured chordwise positions the amplitudes of the summed influences agree almost exactly while there is only a small difference in phase angle (Fig. A4 b) and Fig. A5 b)). From the results above one can conclude that the superposition principle can be validated for this flow case even if there are small differences for transducers close to the leading edge.
The unsteady tests at the flow condition with an higher incidence angle but with a lower Mach number than the previous flow case show larger differences between the reconstructed phase diagrams of the travelling wave case and the single blade vibration case at all transducer positions (Fig. A6 a) and b); Fig. A7 a)). However, if one compares only the influence of a blade upon itself plus the one of the direct neighbor blade (on the suction surface this is ‘m+1’ and on the pressure surface ‘m-1’) one finds an almost perfect agreement between single blade mode and travelling wave mode (Fig. A7 b) and Fig. A8 a)). The reconstruction of the contribution of all other blades with the influence coefficients showed that the shape of the resulting curves for the travelling wave mode and for the single blade vibration mode resemble each other (Fig. A8 b)) in the phase diagram. But, the summed influences from other vibrating blades (except the direct neighbor blade) upon the reference blade are clearly bigger in the single blade vibration mode than in the travelling wave mode for this flow case. It appears that the superposition principle can not be exactly applied in this case, because non-linear effects appear at this high incidence angle.

The same tests were done for a flow case at an high inlet Mach number (Fig. 9). It was found for this flow case that the phase diagrams for the single blade vibration mode and for the travelling wave vibration mode of the cascade show a poor agreement (Fig. A9 and Fig. A10). It is still the best close to the leading edge on the suction surface (Fig. A9 b)) where it was the worst for the other two flow cases. Further downstream on the blade it is seen that even the eigeninfluences agree poorly. For a transducer that is positioned in the region where a shock on the suction surface (SS02; x/c=0.194) is situated it is seen that the imaginary part of the eigeninfluence of the travelling wave mode is positive. This means a damping behavior on the suction surface. The eigeninfluence from the single blade vibration mode on the other hand indicates an exciting influence of the blade on itself. The shape of the phase diagrams and the values that were found for the influence coefficients of the blades show that the blades farther away than the two immediate neighbor blades also have a non-neglectable influence.

The details of this test shall not be discussed in this paper. But, it is seen that for this high inlet Mach number flow case the application of the superposition principle is not valid as it is based upon the linear superposition of the unsteady pressures. Other indications of a non-linear behaviour of the unsteady pressures at high Mach number were found for another experiment. Time dependent pressures were recorded at several amplitudes at an interblade phase angle of 180° with the cascade vibrating in the travelling wave mode. The results showed a dependency of the time dependent pressure amplitudes on the blade vibration amplitudes at some transducer position (Fig. 10). The tests suggest that non-linear effects have to be taken into account.

Fig. 10: Unsteady pressure coefficients for different blade vibration amplitudes (M1=0.981, β1=49°, i1=2.3°, σ=180°)
Summary

Tests to estimate the steady-state and unsteady data spread of results of vibrating cascade experiments show that they are small. An analysis and comparison of the time dependent test data for different cascade vibration modes is possible with a good accuracy.

It was shown that the superposition principle is in general still valid for a flow case with a low incidence angle and a high subsonic inlet Mach number with a small supersonic zone on the suction surface but with no shocks. At a lower Mach number but at a high incidence angle the time dependent pressures caused by the vibrating blades seem not to superimpose in the same way in the travelling wave vibration mode and in the single blade vibration mode for blades that are not part of the same interblade channel. Large differences between the influence of vibrating blades upon a reference blade in the travelling wave mode and in the single blade vibration mode were found for a flow case at a high subsonic inlet Mach number with a shock on the suction surface. It seems that the superposition of the time dependent pressures is non-linear so that the superposition principle can not be applied in this case.

It is concluded that the superposition principle can probably be applied with great accuracy for flow cases with small supersonic and separation zones. But, for cases with high Mach numbers and with shocks in the flow field and for separated flows, the non-linear effects become larger and the application of the superposition principle becomes less accurate. This should also be considered for the time dependent calculations of such flow cases.

Further tests to confirm the observed tendencies that are mentioned above must be done.

Acknowledgments

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