LASER-TWO-FOCUS MEASUREMENTS IN A SUPERSONIC COMPRESSOR STAGE - EXPERIENCES AND NEW DEVELOPMENTS

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Laser-Two-Focus Measurements in a Supersonic Compressor Stage - Experiences and New Developments -

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Abstract

The Laser-Two-Focus Technique (L2F) was applied to analyse the flow field of a mixed flow supersonic compressor. As the performance of an existing L2F Measurement system could not meet the expectations several improvements with respect to the data registration and evaluation have been carried out. The main restrictions of the former system performance were located at the event collecting unit and the system's control unit. They were replaced by a digital signal processing unit and a personal computer system. This exchange did not only solve the problems of the substituted system, but it also opened new ways for an easy to operate and informative measurement system and allowed the development of new algorithms to automate the measurement process. The new concept led to a substantial decrease of measurement time while increasing the reliability of the taken data.

Introduction

Highly loaded transonic and supersonic compressors seem to meet the future demands in the development of small gas turbines and jet engines. The design of a mixed flow supersonic compressor rotor was presented by [Mönig et al. /93].

Detailed experimental investigations of the rotor flow and the stage performance have been carried out during the last year. The flow in the mixed flow supersonic compressor is characterized by narrow flow channels, high velocity gradients due to shock and expansion wave systems and a high rotational speed.

As any conventional probe measurement causes considerable blockage and also interferes with shock waves, there exists a strong demand for a non-intrusive measurement technique such as laser anemometry. Beyond that, only laser anemometry offers the possibility of measurements in the rotor blade passage.

The decision to the credit of the Laser-Two-Focus Technique was taken because of its superiority over the Laser-Doppler-Velocimetry (LDV) in the following fields [Kiock/84]:

- higher optical resolution due to small focus diameter and beam separation,
- lower influence of reflections of side- and backwalls due to shorter length of measuring volume,
- smaller detectable particles, which are able to follow the strong flow accelerations and decelerations in the transonic flow.

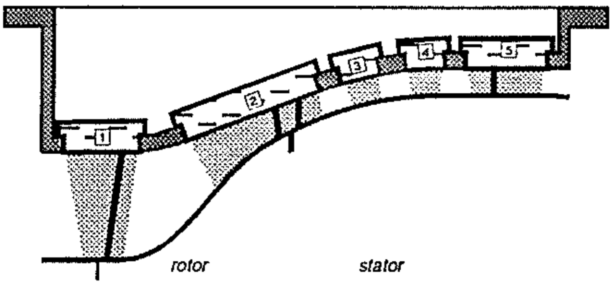

Figure 1: Optical access to the flow path of the mixed flow compressor stage

The optical access to the flow path of the supersonic compressor was gained by several glass window, inserted in the compressor casing. The demand of plane surfaces due to optical reasons led to a restriction of the accessable region of the flow path.

The Laser-Two-Focus Technique

The Laser-Two-Focus Technique determines the amount and the direction of a flow vector by observing light reflected by small particles travelling with the flow. This is achieved by correlating the reflection signals of both focal points of a splittered laser beam.

To distinguish between correlated events, generated by a unique particle passing start and stop focus, and uncorrelated events, generated by two independant particles, the data have to be evaluated by statistical means. In turbomachinery applications the method of collecting flight events in histograms is a reliable method to evaluate the data.

A complete L2F measurement consists of a certain amount of histograms, measured at different angular positions, each containing probability distributions of a certain quantity. At the mean direction of the flow it is more likely to have correlated events, so the probability density of the corresponding histogram is higher than those measured at nearby angular positions. Each valid histogram shows the probability density of a Gaussian distribution. Its average value gives information about modulus and angle of the flow vector and its standard deviation represents the level of turbulence.

There are two ways to analyse the histograms: All histograms of a position can be arranged in a two-dimensional histogram, or the histograms can be accumulated into two marginal distributions [Schodl/91].

The 2D-method is a very accurate way to analyse the data, but it takes a huge amount of flight events. The result of the marginal distribution method implies certain errors in flows with high level of turbulence, but needs a much fewer number of events than the 2D-method to produce results with a comparable statistical uncertainty.

A very important assumption for the accuracy of both procedures is, that the number of start events each histogram is based on, is identical for every angular position.

In the periodical unsteady rotor flow a method called multi window technique [Schodl/81] is used to divide the blade pitch in a fixed number of segments named time windows. For each time window there is a related histogram. Flight events are collected in that histogram, which corresponds to the time window of the occurrence of the event. This leads to a measurement of up to 16 different histograms simultaneously.

The set-up of the Laser-Two-Focus System

A Laser-Two-Focus System can be divided into 4 sub-systems:

1. The optical set-up,
2. the analogue signal processing unit,
3. the digital signal processing unit,
4. the control unit for the measurement system.

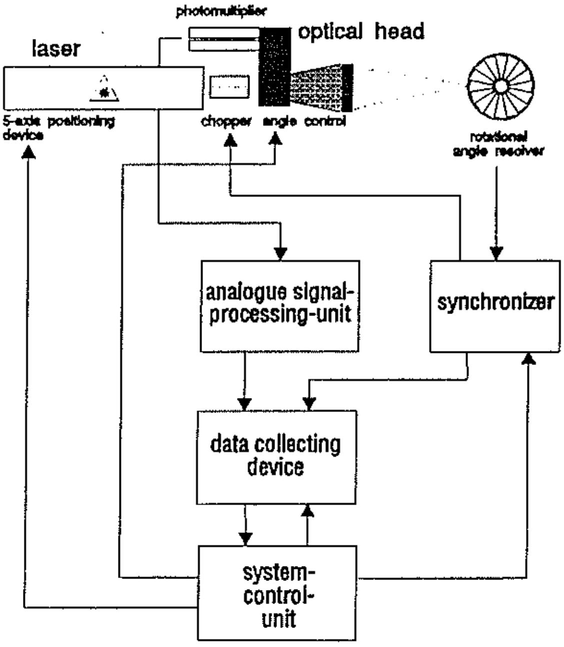

Figure 2: The set-up of a Laser-Two-Fokus-system

The optical set-up

The optical set-up consists of an Argon-Ion-laser light source, a light chopper, an optical head and two photomultipliers. The optical head splits and focuses the laser beam. It also directs the reflected light to the photomultipliers. The optical head has a focal length of $350mm$, the distance between the two foci is $164\mu m$ and its focus diameter is $8\mu m$.

The analogue signalprocessing unit

The electrical impulses produced by the photomultipliers are amplified and formed by the analogue signalprocessing unit in order to produce defined time marks. This unit also converts the time between the start and stop time mark in a voltage, which is converted into a digital value by a high speed analogue/digital-converter. This hardware is able to process flight events with a maximum data rate of $250kHz$.

The digital signalprocessing unit

The digital signal processing unit consists of two devices: The synchronizer and the data collecting device. The synchronizer produces a digital information about the circumferential position of the rotor to define the time windows and to reduce the laser power during the blade passage. The data-collection unit is responsible for the registration of flight events in histograms.

The system control unit

The system control unit controls the devices involved in the measurement process. Also it acts as an interface to the operator. It should assist the operator by giving him informations about the system's condition and the progress of the measurement. Also it should relieve the operator by automating the measurement process.

A concept for the event collection device and the system control unit

Introductory investigations came to the conclusion, that especially for multi window measurements, the conventional realizations could not satisfy the expectations on the performance:

- The event collection device needed too much time to compute events. It processed event data based on 8Bit-registers.
- The number of events are not independantly selectable for each time-window. There is only one counter to control the number of events for all windows, so measurements cannot be based on a defined statistical uncertainty.
- The control unit supplies the operator with very few visualization and information during a measurement.

To solve these problems a new concept for the digital signal processing unit and for the system's control unit was created.

Using a digital signal processor for the event collection task

Conventional realizations of the event collection device are not able to process the maximum data rate produced by the analogue devices. Also they are not specialized to handle the requirements of multi window measurements.

Thus a new concept for an event collection unit based on a digital signal processor (DSP) is presented here. A digital signal processor is a special kind of microcomputer device, which is optimized for digital signalprocessing like digital filtering, voice de- and encoding, FFT and image processing.

As a digital signal processor the Texas Instruments TMS320C25-50 processor was chosen. It is a second generation, 16 bit integer processor, which has a peak performance of 12.8 MIPS and a cycle-time of 80ns. It is located on a board for the extension slot of an IBM-compatible computer.

This data collection unit is able to control the recording of flight events on dependency of the number of events registrated so far and handles this task for up to 16 histograms independently.

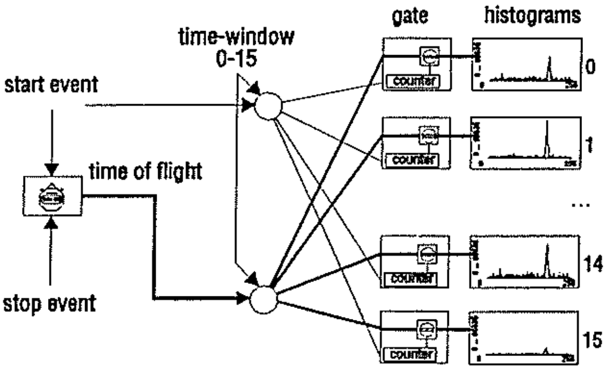

Figure 3: Sketch of counter controlled flight event registration for multi window measurements

The software running on the DSP manages the histograms and their event counters in its memory. The program of the signal processor is divided into two independent subprograms, which are activated by hardware interrupts. The first part counts start events in one the 16 counters, related to the time window they were originated. The second part of the program is activated by a successfull flight event. It checks the start event counter corresponding to the time window. If the counter has not reached a preset limit, the digitized time of flight is recorded in the matching histogram.

This task is performed very fast by the digital signalprocessor; the updating of a counter is completed in approximately 1.6μs. This is shorter than the time needed by a particle to travel from spot to spot plus the time consumed to digitize the time of flight. The recording of time of flight in histograms, gated by the counters, is performed in about 1.8μs. This hardware achieves the adaption of the processing time to the data rate of the analogue system. So the data collection unit is no longer a restriction in the chain of data processing of the L2F System.

An important benefit of this hardware is the independant management of each time window. The distributions contained in each histogram are based on a well defined number of events so the data evaluation can easily calculate the flow parameters based on a known statistical uncertainty.

Another advantage of this way of realization is the tie-up to a host computer system. While a measurement is running, the host computer can download preliminary histograms from the memory of the digital signal processing system. This transfer is performed very fast via the extension bus of the host, so the delay in the process of measurement is negligible.

New concept for the system control unit

In the field of Laser-Two-Focus Measurements the system control unit has a very important duty. It is responsible for the control of the L2F hardware components in the system and it manages the organization of the mass storage system to save and document the data. Also it performs as an interface between operator and measurement system, which should offer informations about the measurement system's condition.

For this job an IBM-compatible personal-computer based on a INTEL 80486 was chosen, because of its good performance, its flexible systembus, its wide range of software support and its low price. On the basis of IBM OS/2, a true 32bit multitasking operating system without any memory limitations, which offers a sophisticated graphical user interface and a very flexible applications programmers interface (API), a L2F control application was developed in the C++-programming language.

The application is divided into different layers. The lowest layer consists of device drivers to control the hardware directly. On top of this layer there is the application layer composed of different tasks. A background task receives preliminary histogram data from the data collection unit and processes it for display and validation purposes. Independent of this task, a parallel task is responsible for user interaction and graphical presentation of the histograms. This task communicates with the user by a number of windows on the display screen.

So the operator gets a lot of information about the L2F System at a glance. The applications main window, in figure 4 partly hidden by other windows, offers informations about system parameters, like measurement position, synchronizer status, and other pre-settings. These parameters can be changed by use of easy to operate dialog boxes.

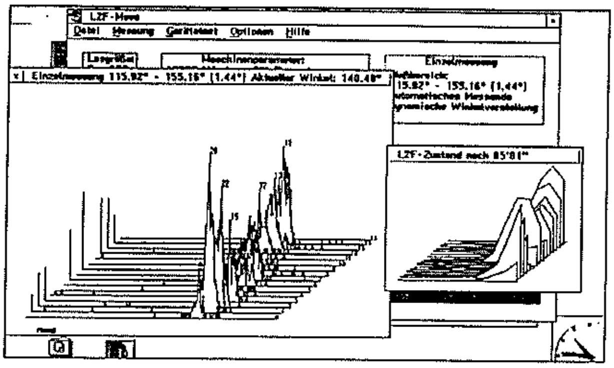

Figure 4: Screenshot of the L2F system control application while a measurement is performed

While a measurement is performed, two other windows give additional information. The first measurement window, shown on the left of figure 4, displays the status of the actual angular position. This is done by presenting the 16 preliminary histograms of a blade's pitch at the actual angular position in a 3D-manner. On the horizontal axis, the time of flight is shown, the vertical axis shows the number of events, the z-axis shows the time-windows. At the origin of the co-ordinate system of each histogram, there are bars, which indicate the status of each start event counter. The second window on the right of figure 4 gives an overview over the histograms of all angular positions so far. It presents the marginal distributions accumulated over the time of flight for all time windows and angular positions as a 3D-graph. Here the horizontal axis shows the angle, the vertical axis shows the marginal distribution and the z-axis shows the time windows. Alternatively the left window of figure 4 can present the histograms as marginal distributions accumulated over the angle. This helps the direct estimation of data intended to be analyzed by the marginal distribution method, because in a normal representation these distributions are not very distinct, due to their lower number of start events. The advantage of this application is an easy to operate and informative measurement system. Because data intaking and preprocessing task are separated from the display and interaction task, the system-overhead is very low and measurements can be performed with maximum speed. Based on the new concept of hardware, new ideas to improve the system performance could be realized.

Advantages in measurement procedures

Better exploitation of the resolution of the synchronizer unit

The synchronizer unit divides the blade pitch into 32 segments. These positions can be mapped to 16 time-windows, which are connected to histograms.

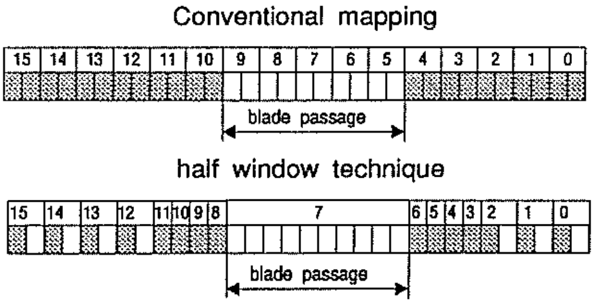

Figure 5: Example of the relation between synchronizer position and time window using the conventional and the half-window method

Conventionally this is achieved by mapping two positions to one time window. This is illustrated by the upper sketch of figure 5. The angular resolution of a time window is 1/16 of a blade pitch.

When measuring in the rotor section the laser has to be switched off because of the blade's passage through the laser beam. The corresponding windows can not record any valid data. Thus, depending on the blade's thickness, the number of usable windows is reduced.

As a solution to the reduction of angular resolution the half window method was developed.

Using this method only every second position is mapped to a time window. The time windows, which would normally fall into the blade passage are arranged with a 1/32-distance to the area of interest. So this area can be divided into smaller steps which is of special interest regarding the resolution of a transonic flow field with its strong gradients. By default the system software arranges these windows symmetrical around the blade passage trash-window.

All remaining positions are mapped to a single histogram. This histogram is called trash window. This window collects all unwanted flight events and is not used for data evaluation. The example shown in figure 5 uses time window 7 as a trash window.

As a result, the width of the time windows are half of the conventional time-windows. This leads to a doubling of the system's resolution, because the system averages flight events over the width of a time-window. So strong gradients of the flow vector can be resolved much sharper.

Also the measurement always produces 15 histograms of a blade pitch. In contrast to that the conventional method would only produce 11 histograms.

As a disadvantage this method doubles the measurement time theoretically, but due to the system overhead at the beginning and the end of a measurement this factor lowers to roughly 20 – 30 percent. Also in the most applications this disadvantage is less important than the advantage of a higher resolution.

New measurement-control with an active feedback

The Laser-Two-Focus System can show its efficiency, if an automatic measurement procedure is used. This means, that the system control manages the measurement of distributions at different steps of an angular range without the interaction of an operator.

The data evaluation needs a complete measurement for one time window containing a number of histograms measured at different angular positions. This range is located around the mean direction of the flow in each time window. The histogram of the mean direction shows an absolute maximum in its distribution, the others show smaller distributions. Normally the data evaluation needs all histograms of an angular range until its value has dropped to 10 percent of the maximum measured at the mean direction of the flow.

The duration of a measurement of a distribution depends only on the seeding quantity and the number of start-events but not on the angular orientation. Therefore the measurement time is proportional to the number of angular steps and to the seeding quantity at the worst time-window of the blade pitch.

So the definition of the angular range is a very difficult process, which influences the quality and performance of the L2F very intensively. If the range is selected too small, the data are worthless, because the data evaluation fails to analyse it. If the range is too wide, measurement time is increased without any purpose.

So a method of estimation of the preliminary histograms was implemented in the process of data collection. This was made possible by the good chain up of the data collection unit and control unit.

An estimation of the preliminary histograms is accomplished by setting the marginal distribution, integrated over the time of flight dimension, into relation to the pre-setted number of events. If this value does not reach a certain limit, the time window is terminated immediately, that means it is not taken into consideration for waiting to reach the counter limits.

Additionaly another algorithm increases the stepping angle if the data registration of all time windows were terminated by that estimation.

This technique reduces measurement time substantially, because the measuring system does not waste time on waiting for the completion of measurements in angular areas which wouldn't influence the result. Experiments showed, that under normal conditions, measurement time could be reduced for 40 percent, while having no loss in the quality of the data. Also the definition of the angular range can be taken much more generously. This leads to an higher reliability of the taken data.

Experiences

Measurements in the mixed flow compressor

Using the described hardware components and the software application first measurements in the rotor blade passage have been carried out. The experiences, made while measuring the flow, influenced the development of the system control application.

At the beginning of the measurements three scopes for the success of the measurement were found to be essential:

- seeding of the flow,
- angular resolution power,
- signal/noise ratio.

Due to aerodynamic reasons the mixed-flow compressor is operated in a closed loop. So the fluid is very clean and without an artificial seeding L2F-measurements were impossible. A seeding generator, which atomizes a DEHS-oil (boiling point: 256^oC), produces particles in the size of 0.1 to $0.4\mu m$ with a rate of 10^9 particles per second. The seeding is added to the flow approximately $1m$ upstream the rotor inlet in the plenum chamber. The access to the flow can be changed in circumferential and radial position.

An outstanding experience concerning the seeding was that its quantity decreases downstream. So measurement time increased from inlet area to the inlet of the stator from about one minute to 20 minutes, using 200 to 500 start events per time window. An adjustment of the flow access of the seeding brought only noticeable effects in the circumferential position.

The triggering of the digital rotation angle system was a very delicate task. Errors in that system take influences on the angle resolution of the measurement system. An optical blade detector mounted in the casing combined with an integrating PLL-treatment of the signal produced especially at nominal speed an excellent, jitter-free trigger signal.

Thus the angle resolution fulfilled the requirements to use the half window method.

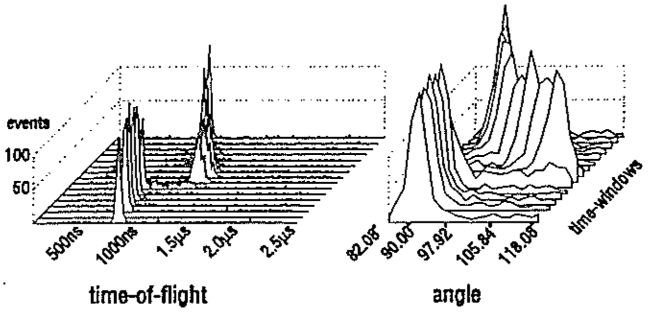

Figure 6: Unprocessed histogram data, representing the flow vector of a blade pitch

As an example for the good angular resolution of the Laser-Two-Focus System, a mid span measurement $6mm$ upstream the rotor blade leading edge is shown in figure 6. The discontinuity in the modulus and the angle of the flow vector, induced by the rotating leading edge shock system, can clearly be identified in the shown histograms.

The left group of histograms shows the marginal distributions accumulated over the angle, containing the information about the modulus of the flow vector. The right group are marginal distributions accumulated over the time of flight. They show the direction of the flow vector. The abrupt change of the flow vector modulus and angle between the seventh and the eighth window indicates the position of the leading edge shock. The increased noise level in the seventh window is due to a slight non periodical shock movement caused by unsteady flow phenomena.

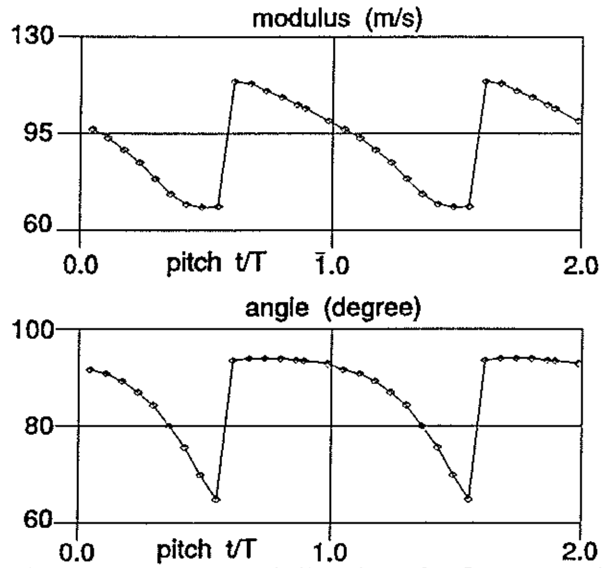

Figure 7: Amount and direction of a flow vector in dependency of the blade pitch

Figure 7 shows the amount and direction of the flow vector versus the blade pitch. The rotating shock system can clearly be seen by the discontinuity in the modulus and flow angle. The difference between the angular range of figure 6 and figure 7 is caused by different co-ordinate systems of the Laser-Two-Fokus System and the compressor.

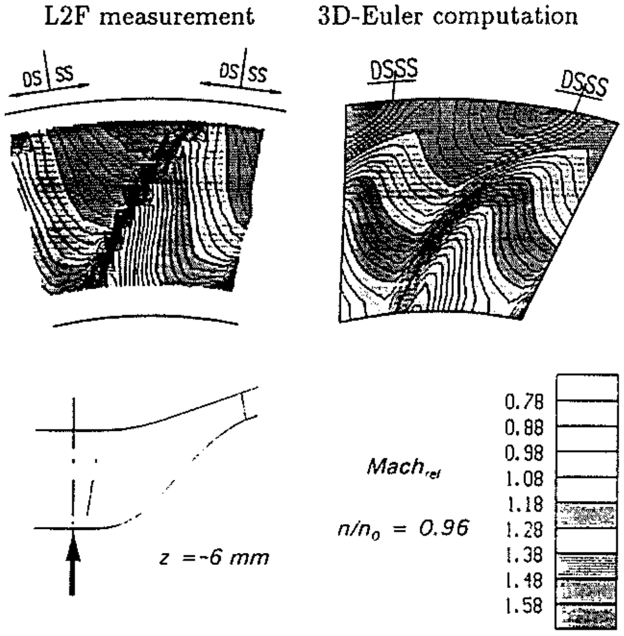

Figure 8: Measured and predicted Mach number distributions

Figure 8 illustrates the velocity distribution $6mm$ upstream the rotor blade leading edge by means of relative Mach number contours. The measured locations of the shock system and the subsonic region close to the hub show good agreement in comparison to the results of the 3D-Euler-Computation. However, the signal/noise-ratio was found to be very bad near the hub and the casing, due to scattering at the backwalls and the glass windows. Especially close to the hub the signals did not meet the requirements of the data evaluation although the hub was blackened. Thus, measurements in close vicinity to the hub will be subject of future improvements of this L2F-System.

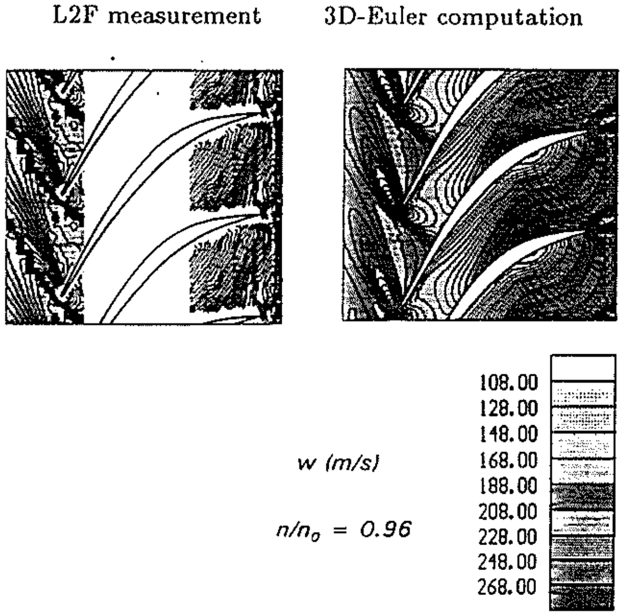

Figure 9: Measured and predicted velocity distributions (mid span)

Figure 9 finally shows the measured and computed blade-to-blade velocity contours of the rotor at mid span. The shock is located close to the leading edge of the rotor blades. The L2F measurements confirm the computed shock position very well. The measured incidence angle in the rotor inlet area is slightly higher than predicted and results in stronger flow acceleration around the leading edge and consequently higher velocities in front of the shock. The results of these measurements in a transonic flow field with strong gradients confirm the performance and the high resolution of the L2F-System in an impressionable manner.

Conclusions

The event-collecting-device and the system control unit were identified as the weak points of an existing Laser-Two-Focus system. By a replacement of these two components, using a more suitable technical solution, the former restrictions were cleared out.

Additionally this hardware concept opened new ways to increase resolution, usability and automation of the measurement system. Especially the improved usability and automation led to a substantial decrease of measuring time and to an increase of the reliability of the taken data.

The improvements of the system control unit opened new opportunities to increase the efficiency and to simplify the operation of the Laser-Two-Focus System.

Measurements in the mixed flow supersonic compressor stage using this improved Laser-Two-Focus System yielded detailed flow information. They proved the excellent performance and resolution of the Laser-Two-Focus System.

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