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A FUZZY CONTROLLER TO BALANCE PNEUMATIC MULTI-HOLE-PROBES

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A FUZZY CONTROLLER TO BALANCE PNEUMATIC MULTI-HOLE PROBES

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Abstract

Pneumatic multi-hole probes are still an important tool in order to investigate (steady) flow profiles of turbomachines and cascades. Therefore – depending on the kind of calibration – the approximate or exact balance of the yaw angle is necessary. This paper presents a software controller which turns the probe against the flow direction within a few steps. The calculation of a control step is based on fuzzy sets [1]. The controller works independent of the Machnumber and has a control range of about ±100° with the use of a 70°-cone probe. Outside of the control range a search algorithm allows using the probe also in regions of wake and reverse flow. The required time for the balance was reduced to half compared to manual balancing.

Nomenclature

c	m/s	flow velocity
C_{mach}	$(p_1 - p_m)/p_m$	Machnumber coefficient
C_{pitch}	$(p_4 - p_5)/(p_1 - p_m)$	pitch angle coefficient
C_{yaw}	$(p_2 - p_3)/(p_1 - p_m)$	yaw angle coefficient
D_{alpha}	°	control action (control step)
F_{pdyn}	$(p_t - p_s)/(p_1 - p_m)$	dynamic pressure coefficient
F_{ptot}	$(p_1 - p_t)/(p_1 - p_m)$	total pressure coefficient
Ma	-	Machnumber
p_{difp}	$p_2 - p_3$	yaw pressure difference at the probe
p_{dynp}	$p_1 - p_m$	dynamic pressure at the probe
p_{hypo}	see text	hypotenuse pressure at the probe
p_m	$(p_2 + p_3)/2$	mean pressure of the side holes
p_s	Pa, kPa	static pressure
p_t	Pa, kPa	total pressure
$p_1 .... p_5$	Pa, kPa	probe pressures
Z	0 ... 1	degree of membership
α	°	yaw angle
β	°	pitch angle

1 Introduction

With pneumatic multi-hole probes the velocity, its direction and the static pressure in a flow channel can be recorded. Figure 1 shows such a probe.

Before using the probe a calibration is necessary, which can either be two– or three–dimensional. Depending on the kind of calibration, the yaw angle must be balanced either exactly (2D-calibration) or approximately (3D-calibration), so that the measured pressures are in the range of the calibration. Therefore the probe has to be turned against the flow direction, until the amount of the yaw angle coefficient is lower than a limiting value. To make sure that the probe stays against the flow, the Machnumber coefficient has to be positive.

In order to install a fully automatic measuring tool a balance controller is needed. For this task a software controller was developed. It calculates the control step out of two measured values and needs only a few steps for the balance. Therefore it uses a heuristic matrix as data base to coordinate both measured values. Existing controllers [2, 3, 8] normally work with only one measured value, as the control range is restricted or the controller has to be adjusted for the actual Machnumber. The following chapters explain the working principle of this fuzzy logic controller.

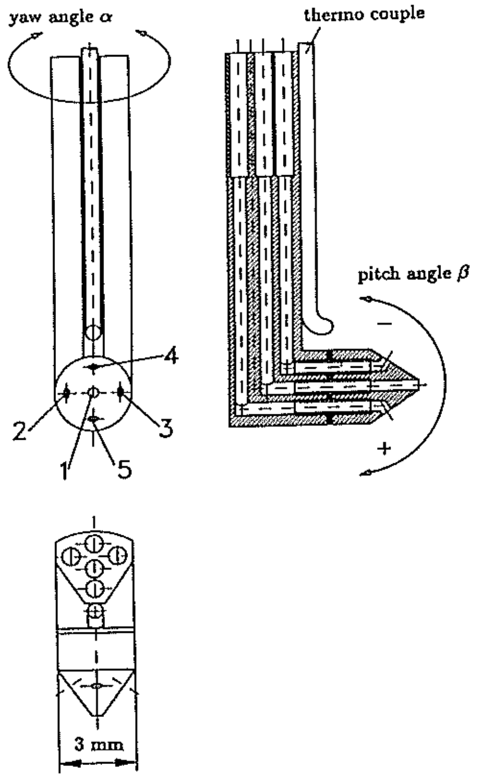

Figure 1: pneumatic five-hole cone probe

2 Recording the control characteristic

The control characteristic depends on the probe's shape. It has to be recorded once for any probe type. To estimate the actual status of balancing the yaw angle pressure difference p_{difp} and the apparent dynamic pressure measured at the probe p_{dynp} are used. Therefore only two pressure transducers are needed:

$$p_{difp} = [p_2 - p_3] \tag{1}$$

$$p_{dynp} = p_1 - p_m = p_1 - \frac{p_2 + p_3}{2} = [p_1 - p_3] - \frac{p_{difp}}{2} \tag{2}$$

The fraction of both pressures is the yaw angle coefficient, which is linear for the upper cone probe in the range of about ±12° around the exact balance point, and it is practically independent of the Machnumber.

$$C_{yaw} = \frac{p_{difp}}{p_{dynp}} \tag{3}$$

To get the control characteristic the probe is turned in roughly 8° steps from −180° to +180° and the pressure values of p_{difp} and p_{dynp} are recorded. In the following the *double value* of p_{dynp} is used in order to assimilate the level of both quantities, see figure 2.

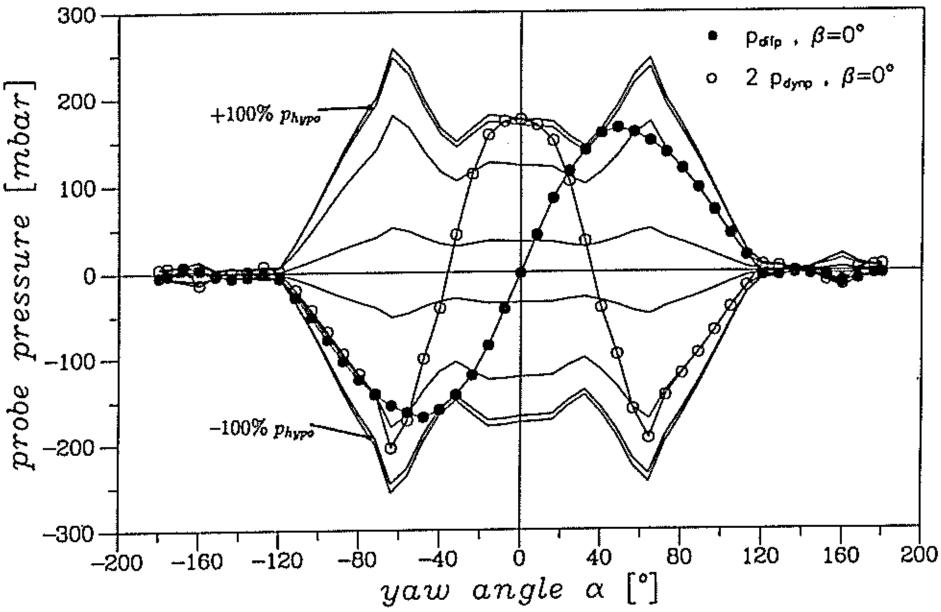

Figure 2: pressure curves from −180° to +180° at Ma=0.41

One of these curves is similar to a sinus, the other to a cosinus. Therefore it seems to be obvious to refer both quantities to a common hypotenuse:

$$p_{hypo} = \sqrt{p_{difp}^2 + (2p_{dynp})^2} \tag{4}$$

Now we have got two input quantities between −1 and +1, see figure 3, which are given in the following as percentages.

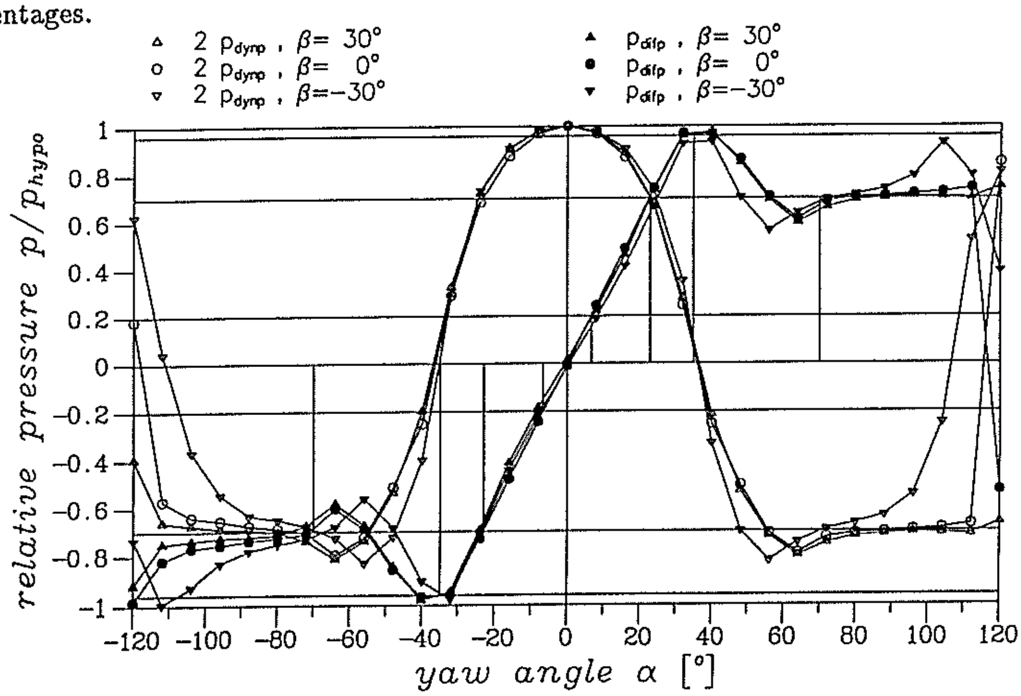

Figure 3: yaw angle characteristic and category-lines of the cone probe at different pitch angles

At the cone probe shown before there are definite values in a control range from -100° to +100°. In the important range between -23° and +23° the curves differ only slightly at different pitch angles and Machnumbers, see figures 3 and 4. The dynamic quantity is symmetrical.

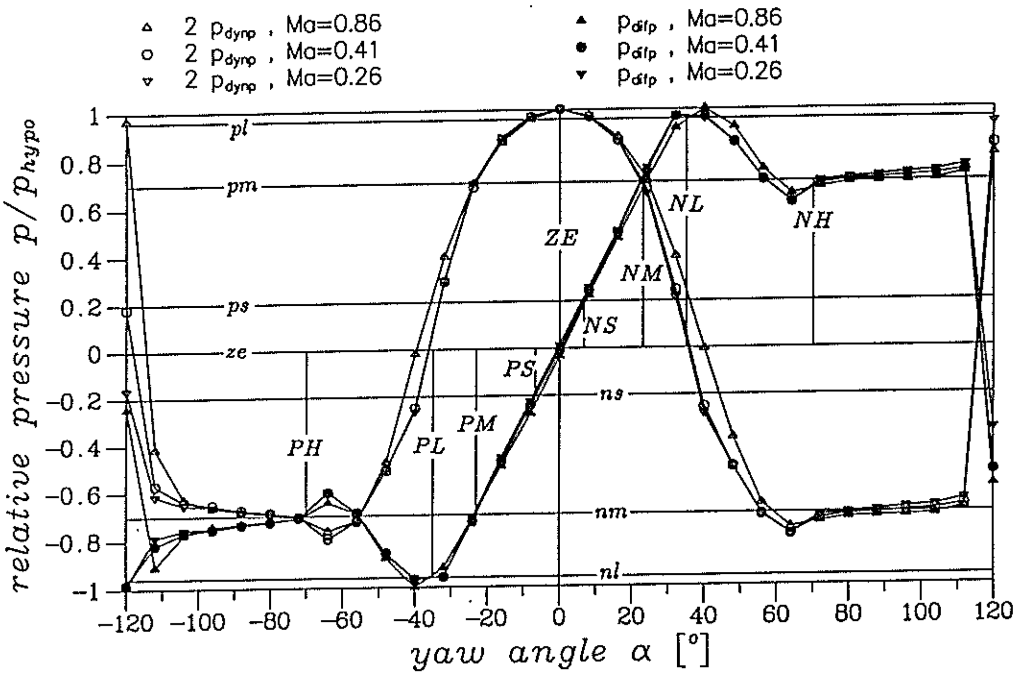

Figure 4: yaw angle characteristic and category-lines of the cone probe at different Machnumbers

For further calculations the two quantities are classified into seven categories (fuzzy state descriptions [4]) between *negative large* and *positive large*, which are drawn into the yaw angle characteristics shown before:

$$nl = -96\%, nm = -70\%, ns = -20\%, ze = 0\%, ps = 20\%, pm = 70\%, pl = 96\%$$

of the hypotenuse. The distribution of these fuzzy state descriptions depends only on the non-linearity of the yaw angle characteristic. With the help of the drawn category-lines the basic control steps between *NEGATIVE HUGE* and *POSITIVE HUGE* (which are also fuzzy state descriptions) can be taken out directly. Therefore we define rules.

Example for a rule:

> if the difference quantity AND the dynamic quantity are both in the category of positive medium, the basic control step for this rule has to be NEGATIVE MEDIUM, i.e. the control step for this rule is -23°.

The basic control steps are later written into an inference matrix (table 1), which is the rule base of the fuzzy controller. Around the exact balance point they should be of high accuracy. Outside this range they are roughly estimated [7], because the maximum control action is limited to ±70°. The basic control steps are:

$$NH = -70°, NL = -35°, NM = -23°, NS = -6.7°$$

$$ZE = 0°$$

$$PS = 6.7°, PM = 23°, PL = 35°, PH = 70°$$

3 Calculation of the control step

When the probe is used for the measurement both quantities p_{difp} and $2p_{dynp}$ are taken and referred to the hypotenuse as usual. Then the *fuzzification* classifies both quantities into all categories from *nl* to *pl*. In the normal case, the categories are not exactly fulfilled. As a consequence the rules have to be weighted. Therefore we define degrees of membership to a category, which are expressed in Z_{pdifp}, Z_{pdynp} and Z_{alpha}, and range between 0 (no membership) and 1 (full membership), see figure 5.

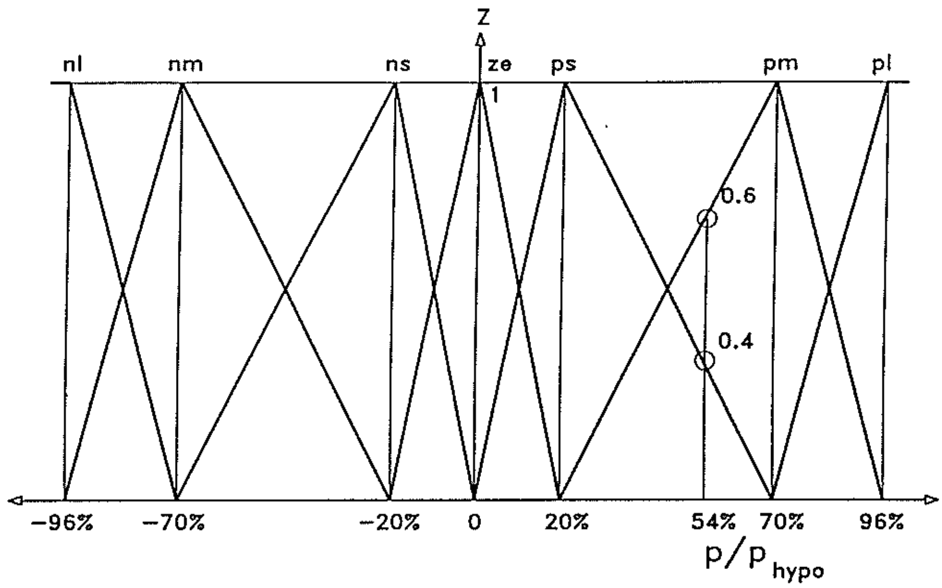

Figure 5: fuzzification: membership function for the quantities p_{difp} and $2p_{dynp}$

Example: If $\frac{2p_{dynp}}{p_{hypo}} = 54\%$ then $Z_{pdynp}(ps) = 0.4$ and $Z_{pdynp}(pm) = 0.6$

The coordination between the two quantities and the basic control steps is fixed into a two-dimensional *fuzzy inference matrix* which was established according to the principle of the missing angle (angle to the exact balance point), see figure 4. With the help of this matrix and with the minimum of $[Z_{pdifp}, Z_{pdynp}]$ – according to an AND-combination [5, 4] – we get for each pair $[Z_{pdifp}, Z_{pdynp}]$ *one* degree of membership to a basic control step $[Z_{alpha}]$.

p_{difp}/p_{hypo}

$2p_{dynp}/p_{hypo}$	nl	nm	(ns)	ze	ps	pm	pl
(pl)	PH	PM	**PS**	**ZE**	**NS**	NM	NH
pm	PL	**PM**	PS	ZE	NS	**NM**	NL
ps	**PL**	PL	PM	ZE	NM	NL	**NL**
ze	**PL**	PL	PM	ZE	NM	NL	**NL**
ns	**PL**	PL	PH	search	NH	NL	**NL**
nm	PL	**PH**	PH	search	NH	**NH**	NL
nl	PH	PH	PH	search	NH	NH	NH

Table 1: two-dimensional fuzzy inference matrix (rule base of the controller)

Example: If $Z_{pdifp}(ns) = 0.87$ AND $Z_{pdynp}(pl) = 1.00$
then $Z_{alpha}(PS) = 0.87$

Then for every category between *NH* and *PH* the maximum is taken (MINMAX-inference). Further explanation can be found in [7].

With the *defuzzification* a crisp (sharp) control action is calculated out of fuzzy state descriptions with the help of a simplified centre of gravity set, see also figure 6. Therefore the basic control steps are weighted with the degrees of membership Z_{alpha} for every category.

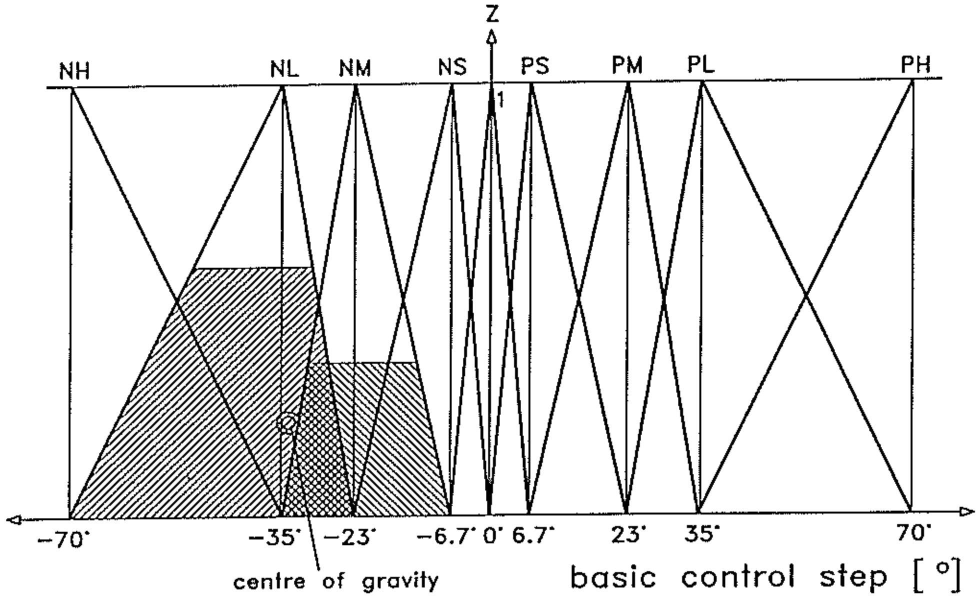

Figure 6: defuzzification

The characteristic of the fuzzy controller is given by the type of the membership functions, its corner values, the structure of the inference matrix and least of all in the base of defuzzification. Abel [5] gives a detailed description of these steps.

The calculation with the help of fuzzy sets can be considered as a kind of coordination of several input quantities and further an interpolation of basic control steps – nothing more. As the difference-quantity p_{difp}/p_{hypo} is linear between *PM* and *NM*, it is comprehensive that an exact balance can be easily achieved (if we have steady flow).

3.1 Supplement of the control step in critical situations

In order to improve the behaviour of the controller in critical situations the preliminary control step value has to be supplied with an adjustment factor. It takes the following aspects into account:

unsteady signals: They may indicate unbalanced pressures. This can be recognized in a large standard deviation of values repeatedly measured. The waiting period is – if necessary – prolonged and the control step is reduced by the factor F_{unst}.

controller stability: For any fuzzy controller an artificial stabilization is reasonable. Therefore at each exeeding step over the exact balance point (p_{difp}=0, whereas p_{dynp} is positive) the control step is reduced by the factor F_{stab}.

reverse flow- and dead zone detecting: If the probe is outside the control range of about ±100°, no balance is possible. This case can be detected, for example with a hypotenuse which is too small. In this case the controller turns to a search modus, the angle step is therefore respectively large (±70°). If no dynamic pressure can be found after a turn of 3 steps or ±210°) an acoustic and optical message is given and an interactive intervention is possible.

decision to run right-hand side or left-hand side: At reverse flow there is an undeceisive range where right drive and left drive neutralize each other. Therefore the degrees of membership to the control steps of one side are ignored.

sudden change of the flow profile: Vortexes that turn up or disappear within a test facility can have noticeable consequences to the measuring section. This case can be recognized in the fact that a steady approach to the exact balance point reverses, i.e. the truncation criterion of the controller worsen sharply. The control routine then restarts.

supervision of the limitation switches: If a control action would nest the probe over the angle limit the control step is either reduced by 25% (F_{limit}) or the position is taken from the other side.

limitation of the number of control actions: If no flow can be found, the controller stops after six attempts.

interactive intervention: If a mistake is found which cannot be corrected automatically there is the possibility to intervene interactively in any phase of the controlling.

Figure 7 shows the scheme of the control circuit for the balance of pneumatic multi-hole probes.

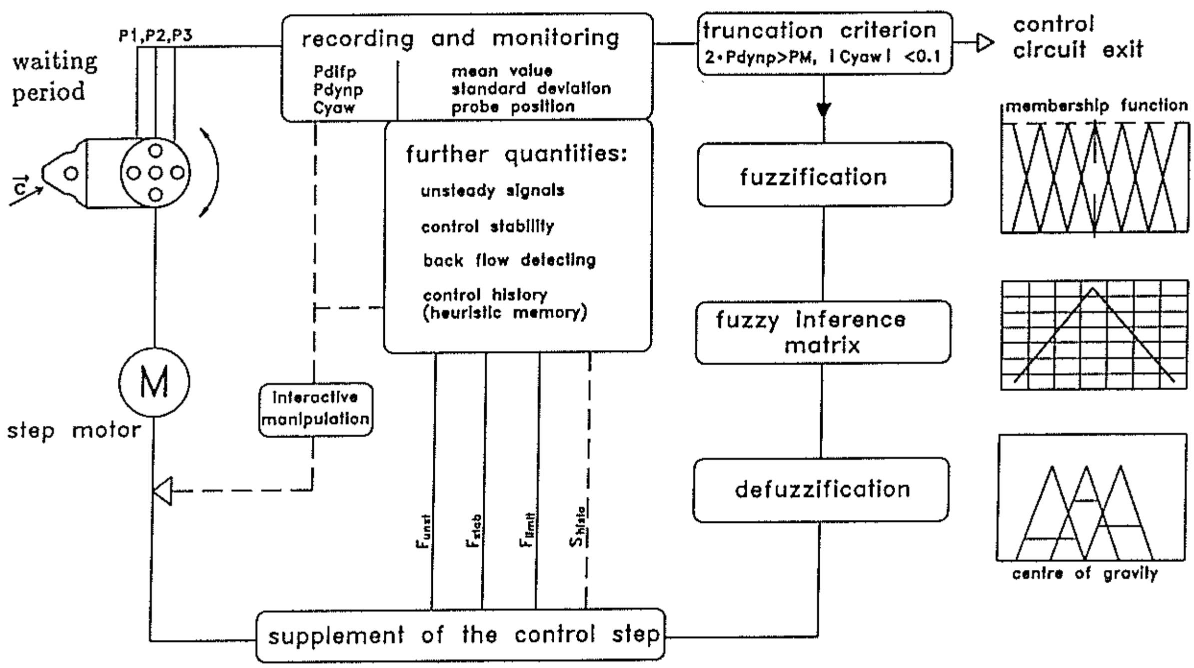

Figure 7: control circuit of the software controller

In table 2 a typical example of the control behaviour is given. It shows that a yaw angle discrepancy of +100° is balanced with an accuracy lower than a half degree, within three control actions in 24 seconds. In this case the waiting period after each control step was 7 seconds, this is necessary for pressure balance. Using fast response probes, the balance can be achieved within a few seconds, depending on the motor velocity.

yaw angle	time	p_{difp}	$2p_{dynp}$	control step
100°	0 s	58.1 mbar	-54.9 mbar	-66.4°
33.6°	8.9 s	139.5 mbar	28.8 mbar	-35.0°
-1.4°	16.9 s	-8.4 mbar	173.5 mbar	+1.6°
0.2°	24.0 s	1.3 mbar	173.8 mbar	(-0.3°)

Table 2: example for the control behaviour

4 Conclusion

The software controller was integrated into a fully automatic measuring system (MESYST), written in FORTRAN 77. The control parameters were confirmed by a computer simulation. The controller has been worthwhile in different usages and in the difficult flow conditions of a decelerated flow in a diffuser (flow separation, reverse flow, high gradients, extrem Machnumber range 0 ... 1.6), right from the start.

The controller is useful for all probes at which a difference-pressure p_{difp} and an apparent dynamic pressure p_{dynp} can be taken. The limits of usage are at very large pitch angles outside of about $\pm 50°$ at the probe shown before. However, the desired control accuracy is only a question of the number of control actions. In normal cases one or two control actions are satisfying. The features of this controller are summarized:

- large control range ($\alpha = \pm 100°$ at the cone probe).
- independence of Machnumber.
- independence of pitch angle ($\beta = \pm 30°$ at the cone probe).
- symmetrical characteristic of p_{dynp}.
- exact balance is possible (when flow is steady).
- quick balance is possible with short pressure tubes and a fast stepping motor.
- reverse flow detecting.
- suitable for different probe types with minimum three holes.
- no effect of different responding times of the pressure transducers, if the waiting period is long enough.
- short development time, easy simulation and optimization.
- easy to install, no special control hardware is necessary.

In two years of experience about 6000 measuring points were balanced by this controller, it proved to be convenient. The duration of the measuring could be halved compared to the manual balance.

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