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OPTIMIZATION OF THE PERFORMANCE OF INTERNAL SIX-COMPONENT STRAIN-GAGE WINDTUNNEL BALANCES WITH FEM

M.Sc. Junnai Zhai
Prof. Dipl.-Ing. B. Ewald
Dr.-Ing. K. Hufnagel
Technical University of Darmstadt, Germany

1. Abstract

The internal strain gage balances are widely used in the wind tunnel as force measuring equipment. One problem during the design of a balance is the conflict between stiffness and sensitivity. In order to overcome this difficulty the balance structures are analyzed with FEM, and then parametric and geometric variations are suggested to improve the stiffness under a given signal.

The stiffness in axial direction is mainly affected by the parallelograms. By using a beam as drag measuring element, the stiffness can be raised by a thicker but shorter and narrower beam. A much better improvement can be reached by using a shear strain element.

The stiffness in normal and side direction is mainly affected by the main beams and the moment measuring elements. Now there are two forms for the main beams: the triangular and the dove-tail matched form. The dove-tail matched form is stiffer than the triangular form. An improvement of the stiffness can be achieved by combining the two forms. The computation shows that the combined form is 21% stiffer than the dove-tail matched form.

Up to now the bending moment is measured through the bending strain. Due to the high stiffness of the shear spring a new moment measuring element based on shear strain has been developed. The FEM computation shows that stiffness in Z-direction can be raised by 65%.

2. Introduction

The success of a commercial airplane development is heavily influenced by the accuracy of force measurements during the aerodynamic development in the wind tunnel. One limiting factor of accuracy is the internal strain gage wind tunnel balance.

The internal balance measures the aerodynamic loads based on the strain caused in the balance body. Thus a deformation of the balance structure is unavoidable. This results in a deviation of the angle of attack of the model during the measurement. A stiffer balance can reduce errors associated with it.

In addition a stiffer balance can raise the nature frequency of the model, balance and sting system, thus the possible vibration of the whole system can be effectively suppressed.

Previous study has shown that the deflecture of an internal balance is a direct reason for the nonlinear interference. So a stiffer balance will reduce nonlinear interference too.

From the above discussion it is known that a stiff balance is very desirable. But due to the compact structure of the internal balance there exists often a conflict between the stiffness and other requirements such as sensibility, interference and sensitivity to thermal effect etc. For example, a high sensitivity is of course expected, in order to raise the resolution and suppress the noise signal in the measuring chain. However, a high sensitivity means at the same time for the current balance configuration also a low stiffness. For the requirements on the linear interference and the sensitivity to the temperature gradients it is the same. Previous study shows that a less stiff parallelogram results in a smaller linear interference on the drag component and smaller error signal due to temperature gradients.

In order to solve such problems the balance structure is analyzed with FEM. From the result of the analysis the balance structure is optimized in two steps. First, the balance structure is optimized by choosing suitable geometrical dimensions. The configuration stays unchanged. Then various new forms for the balance structure are suggested, and they are checked with FEM.

According to the area of applications the internal balances can be divided into transport and combat balances. The requirements on the two balances are different, too. The combat balance is heavily loaded, thus by design the main concern is the load capability (maximal stress). The transport balance is relatively less loaded, but the accuracy requirement is very high. The conflict between the requirement on stiffness and other requirements appears very severe here. Therefore in this study we have concentrated on the transport balance.

The most successfully used configuration up to now for the transport balance is shown in Fig. 1. It consists of four parts: two parallelograms and two main beams. The drag measuring elements are arranged tandem in the parallelograms. The two main beams are dove-tail matched. This structure is very stiff, and it is taken as a starting point for this study.

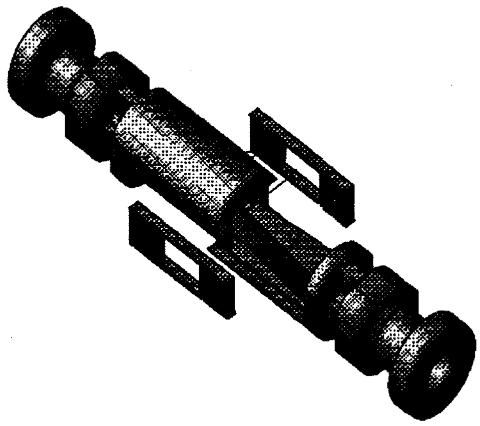

Fig. 1. Components of a transport balance

3. Parametric Investigation

A direct method to raise the stiffness of a balance is to choose suitable dimensions by design. For this purpose the influence of each parameter on the stiffness should be identified.

From Fig. 1 is to see that there are many dimensions needed to define the structure of a balance. These dimensions can be divided into three groups.

The first group defines the geometry of the parallelograms. It includes the thickness (*d*), width (*b*) and height (*h*) of the drag measuring beam and the spacing (*l*) between the two drag beams. The other parameters such as the dimensions of the struts are determined by the signal level.

The second group defines the geometry of the main beams. Most of the dimensions of the main beams are dependent on that of the parallelograms. The only free parameter is the slope of the beams (α).

The third group defines the geometry of the bending moment measuring sections. There are many forms for this section. By different form, the parameters needed are different too.

Due to the complexity of the balance structure the influence of these parameters on the stiffness of the internal balance can only be effectively studied with FEM. For a meaningful comparison the sensitivity stays always constant by variation of the parameters.

3.1 The Parallelograms

The dimensions that define the geometry of the parallelograms influence mainly the stiffness in axial direction. The influence on the stiffness in other direction is very small.

A typical result of this study is shown in Fig. 2. In this figure the change of deformation of an internal balance over the thickness of the drag measuring beam (*d*) is illustrated. It can be seen that the deformation in axial direction sinks with the thickness. But the stiffness in *Y*- and *Z*-direction is almost unchanged.

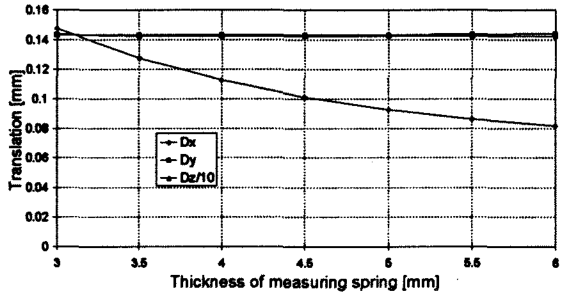

Fig. 2. Deformation of balance over the thickness of drag measuring spring

As a summary it can be said, that the stiffness in axial direction can be raised by using a thicker but shorter and narrower beam as drag measuring element. The spacing between the two drag elements has little influence on the stiffness.

It is worth of noting that with these steps one can raise the stiffness of a balance in the axial direction, but one must put up with the fact, that the interference on the axial component increases, too.

3.2 The Main Beams

The geometry of the main beams affects mainly the stiffness in *Y*- and *Z*-direction.

The result of FEM analysis is somewhat contrary to our intuition. The influence of the slope of the main beams (α) on the stiffness is very small. Only a small increment in the stiffness in *Y*-direction with this parameter can be observed.

An analysis of the deformations of each main beam shows, that this is caused by the bending of the tongued beam in transverse direction, as shown in Fig. 3.

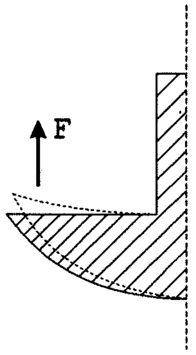

Fig. 3. Deformation of the tongued beam in transverse direction

With the increase of the slope the stiffness of each beam is raised, but the deformation shown in Fig. 3 increases, too. Thus the stiffness of the whole balance is almost unchanged.

3.3 The Moment Measuring Element

All the components except the drag are measured at this section. In order to get enough signal for the measurement, this section is weakened. But the deflection of this section has a great influence on the stiffness of the whole balance, because a small slope at this section would cause great deformations at the model flange due to leverage.

In the development of internal wind tunnel balances various forms are used. For the measurement of the bending moment octagon, cross and cage etc. are created. These forms have different sensitivity and stiffness.

Assume that the bending stress is distributed linearly in the cross-section, according to the linear bending theory in mechanics, one can get the relationship between the slope ($\Delta\theta$) and the maximal stress (σ) which is proportional to the signal. This relationship can be written as:

$$\frac{\Delta\theta}{\sigma} = \frac{2L}{Eh} \qquad (1)$$

Where L is the length of this section, h is the height of the cross-section and E elastic module.

It can be seen from this equation (1) that under the condition of a constant signal the slope depends only on the length (L) and height (h) of the cross-section. In order to raise the stiffness one can reduce the length or enlarge the height.

The first possibility, to reduce the length, is limited by the fact that there should exist enough place for the application of strain gages. In addition, if this section is too short, the strain gages may be affected by the notch stress. This would cause nonlinearity in the signal.

For the second possibility, if one enlarges the height, the moment of inertia increases and the signal decreases. To maintain a constant signal the other dimensions of the cross-section must be reduced. Therefore the cross-section which has more possibility in adjusting the moment of inertia can be dimensioned to its maximal height, and thus be stiffer. From this point one can design a stiffer balance by using a cage than using a cross.

4. Investigation of New Forms

It can be seen that with the above steps it is possible to raise the stiffness of an internal balance, but these steps have some disadvantages. First the improvement is relatively small. Second the improvement is achieved at the sacrifice of other important qualities such as interference. Therefore we should investigate new forms for the internal wind tunnel balance. These forms may have a bigger influence on stiffness than the dimensions of the common one's.

4.1 Drag Measuring Element

Many drag measuring elements have been invented during the development of internal wind tunnel balances. Mostly used are beams of various forms. According to the interference of other loads they can be divided into coupled and decoupled elements.

The first used drag measuring element is the decoupled form. In order to reduce the influence from other components on the drag, the drag measuring element is connected by a relative thin beam to the main beam that works like an elastic joint, so that it can only be loaded by an axial force.

Later it was found that the decoupling is somewhat unnecessary, especially in the case of tandem arrangement of drag elements, because the influence from other components can be compensated by suitable arrangement of drag bridges. Thus the coupled element is used. It is connected directly with the two main beams. The measuring element can be simply a beam with constant cross-section or a beam with variable cross-section to have a constant bending stress.

Because the coupled element can be loaded by force or moment in all directions, a balance using coupled beam as drag measuring element is stiffer than using decoupled beams.

All these elements have one in common, i.e., the drag is measured through bending stress. The disadvantage of these elements is the low stiffness.

Compared with the bendig spring, the shear spring is much stiffer. Therefore a reasonable solution for high stiffness would be to design a shear spring as drag measuring element.

A simple shear spring is designed to measure the drag (Fig. 4). It looks like a coupled beam, only in the middle where the strain gages are to be applied, it is dimensioned very thin, so that in this section there is enough shear stress.

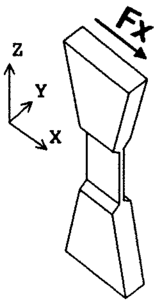

Fig. 4. Shear spring used to measure drag

In order to identify the effect of the shear spring two balances are designed. They have the same dimensions except for the drag measuring elements. One uses a coupled beam and the other uses the shear spring as drag measuring element. The signal stays of course constant.

The two balances are computed with FEM. The calculated deformations are compared in Fig. 5.

It can be clearly seen from this figure, that by using shear spring as drag element the deformation in axial direction is reduced by 60%. The deformation in *Z*-direction is almost unchanged. The deformation in *Y*-direction is slightly greater (1.5%). This is caused by the small load capability of the shear spring in *Y*-direction.

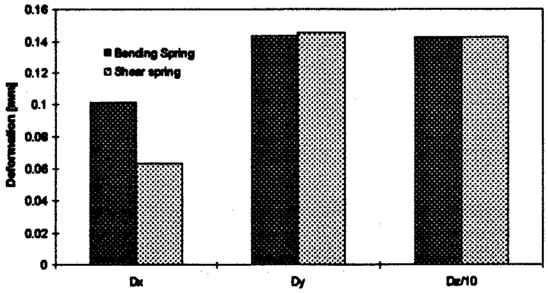

Fig. 5. Deformations of a balance using bending spring and a balance using shear spring as drag measuring element

Besides high stiffness a balance with shear spring as drag element has a small linear interference too. This is because the shear spring is only sensitive to the force in axial direction, while the bending beam is sensitive to both the force in axial direction and the bending moment in *Y*-direction. In addition, there are shear strain gages where two strain gages are manufactured side by side in one piece of base film. By application of such strain gages the influence of the positional errors is small, and consequently the linear interference from this source is small.

4.2 The Main Beams

The form of the main beams has a great influence on the stiffness. The first form of the main beams was a constant cross-section. Though this is simple to manufacture, the stiffness is very low. Later this form was replaced by the triangular form. In this form the change of cross-section matches the change of moment better, and the stiffness is consequently high.

Due to the invention of electron beam welded balance concept by **Ewald,** there is more freedom in the design of the main beam forms. Thus a form, so-called dovetail matched (Fig. 1) was invented. In this form the cross-section of each beam has the maximal height, so the stiffness of such balances are very high. A computation with FEM has shown that by the same condition the stiffness in *Z*-direction with the dove-tail matched form is 8.8% higher than the triangular form, if only the active part of a balance (Fig. 6) is considered.

The dovetail matched form has high moment of inertia, while the triangular form matches the change of moment good. It seems that a combination of the two forms would result in a stiffer form.

A realization of this idea is shown in Fig. 7. The tongued main beam is formed to look like a triangle, so that the moment of inertia at its root can be raised. The forked main beam can be strengthened at its root correspondingly.

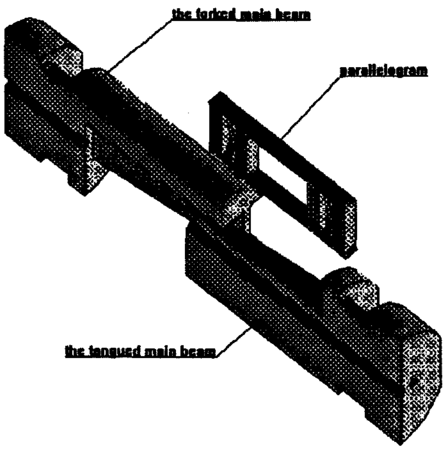

Fig. 6 Balance with main beams of the dove-tail matched is designed for comparison

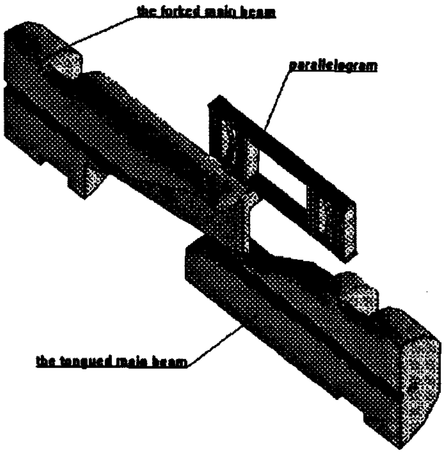

Fig. 7 Balance with main beams of the combined form

In order to prove this idea a balance with main beams of the combined form is designed and computed with FEM. The calculated deformations are shown in Fig. 8. A balance with main beams of the dovetail matched form is used as reference.

It is evident that by using the combined form the stiffness in *Z*-direction is raised by 21%. The stiffness in *Y*-direction is raised by 3%. The stiffness in *X*-direction is unchanged.

The linear interference of this balance is the same as the referenced balance. But the nonlinear interference is smaller due to the higher stiffness.

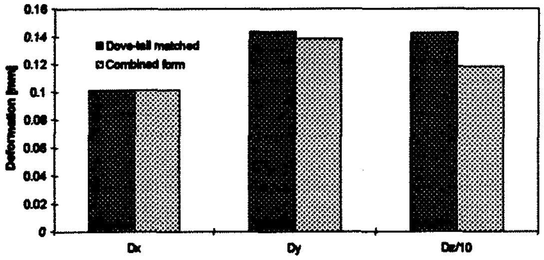

Fig. 8 Deformations of a balance using dove-tail matched form and a balance using the combined form as the main beams

The distribution of von Mises stress in this balance is shown in Fig. 9. Due to the higher stiffness the stress is reduced at the same time. The maximal von Mises stress is 24% smaller than in the reference balance (480 N/mm²).

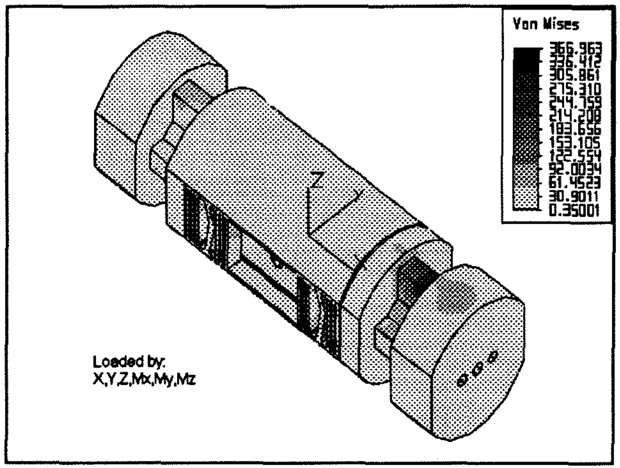

Fig. 9. Von Mises stress in the balance [N/mm²]

4.3 The Moment Measuring Element

As stated above this section has a great influence on the stiffness of the whole balance. Up to now there are many forms which can be used to measure the bending moment. But all these forms use the same principle: the moment is measured by bending stress. It is well known that by an equal signal the shear spring is much stiffer than the bending spring. Thus the stiffness of this section can be raised by using a shear element.

A realization of this idea is shown in Fig. 10. It looks like a cage. The inner part is a solid polygon which undertakes the most bending moment and shear force. The outer part consists of four shear stress measuring elements which are arranged around the solid polygon.

Of the two opposite positioned measuring elements, one will be stretched and the other will be compressed under the load of a bending moment.

This tension or compression causes a shear stress field. By measuring the shear stress with strain gages one can get the moment to be measured.

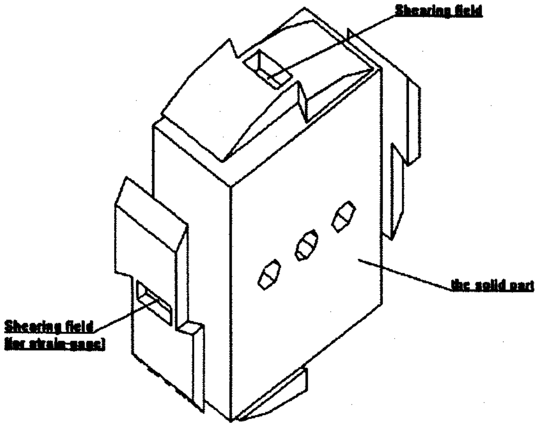

Fig. 10 A moment measuring element using shear springs

A balance using this new bending moment measuring element is designed (Fig. 11). The FEM computation of this balance shows that this balance is very stiff. Under the condition of equal signal the stiffness of this balance in *Z*-direction is 65% higher than that of a balance using a cross as moment measuring element. The stiffness in *Y*-direction is even 88% higher. The stiffness in *X*-direction is almost unchanged. (Fig. 11)

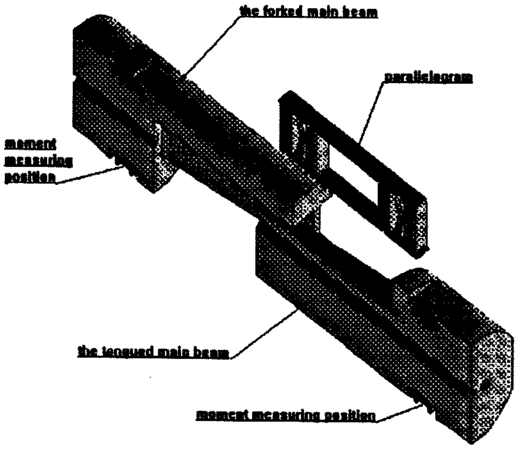

Fig. 11 Balance with shear elements (Detail shown in Fig. 10)

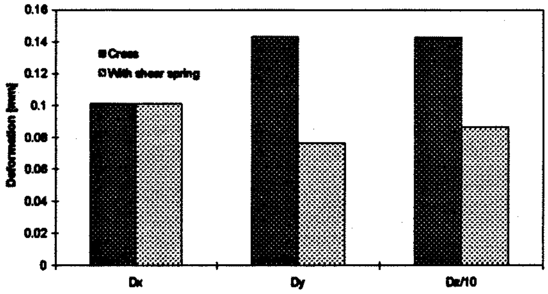

Fig. 12 Deformations of a balance using cross and a balance using shear spring as bending moment measuring element

The von Mises stress in this balance under all loads is shown in Fig. 13. The maximal stress is reduced to 286 N/mm², almost the half of the stress in the reference balance (480 N/mm²).

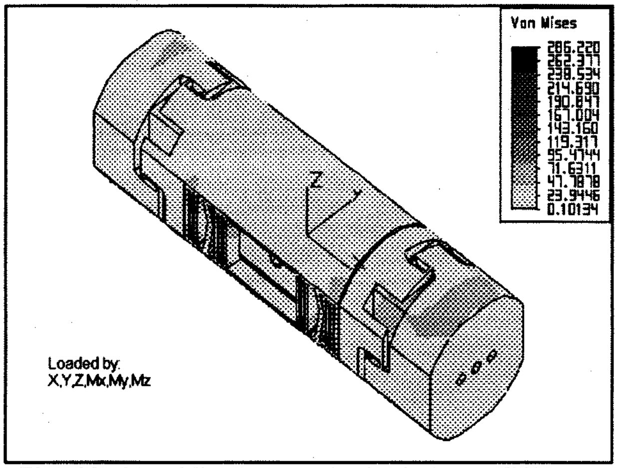

Fig. 13. Von Mises stress in the balance [N/mm²]

5. Conclusions

The stiffness of an internal wind tunnel balance is a decisive factor for quality. In order to get a high stiffness we have tried first choosing the suitable dimensions under the scope of the current balance configuration. With this method the stiffness can be increased, but the improvement is small and it is often achieved by sacrificing accuracy of other properties. Thus we have tried various forms for the balance.

By using shear spring as the drag measuring element the stiffness in *X*-direction can be increased considerably.

By using the form combined from the triangular and dovetail matched form for the main beams the stiffness in *Y*- and *Z*-direction can be increased significantly.

Finally, by using the shear elements to measure the bending moment the stiffness of the whole balance can be improved dramatically.

At least it is worth mentioning, that by these new forms the other qualities of a balance such as interference and stress level are at least unchanged, in some cases they are even improved.

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