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18 "Étude des Capsules Aneroides," by F. Charron, Ministère de l'Air, Paris, France, 1940.

19 "Der Spannungszustand einer Kreisringschall," by K. Stange, *Ingenieur-Archiv*, vol. 2, 1931.

Discussion

J. A. Haringx.[7] The writer was greatly interested in reading this attractive paper, since it contains extensive information on experimental results with various types of corrugated diaphragms, a new mathematical approach taking advantage of the possibilities offered by modern electronic computers, and a number of valuable considerations on work to be done in the future.

Referring to the writer's own work on this subject, it is agreed that from a strictly mathematical point of view the principle of smearing out the effects of the corrugations, which has led to the introduction of a fictitious equivalent flat plate,[8] is only justifiable for a diaphragm with a large number of small corrugations. However, there exist various methods of concentrating the elasticity of structural parts into a number of elastic hinges. It has been shown that by this method very satisfactory results are obtained, even for cases where the number of these hinges is limited to 2 or 3. The writer's experience has convinced him of the same reliability of the smearing-out method. He refers to the elastic stability of helical compression springs[9] and of flat spiral springs.[10] Apart from the approximation based on the smearing-out principle, a more exact method of calculation was derived for these cases, so that the results of the approximation could be checked. Even when the number of spring coils is small, the approximation is surprisingly satisfactory.

Nevertheless, the writer's belief in the smearing-out method when applied to diaphragms having a small number of corrugations has been more or less speculative. He was therefore very glad that in Figs. 15 and 16 the authors published the full deformation of the diaphragm that was earlier investigated by Grover and Bell. Although the profile of this diaphragm is rather unsuitable to be treated in the way dealt with in the writer's paper,[8] he thought it worth while to check the vertical deflection W derived on a sound mathematical basis with the deflection y given in Equations [31] and [32] of the said paper.[8]

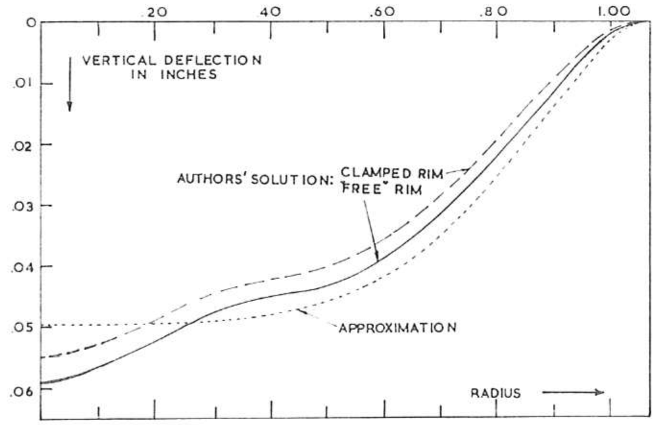

Fig. 21

For the region with uniform corrugations, the quantity q is 8.78 (see reference 2 in the writer's paper[8]) and as shown in Fig. 21 the curves for the vertical deflection are nearly the same, even for this "unsuitable" diaphragm.

The difference in nature of the curves results from the different ways of dealing with the central part of the diaphragm. In the approximation the corrugations are tacitly extended to the center where they are so stiff that this region can more or less be regarded as a rigid flat plate. The authors, on the other hand, treat the central region as an elastic flat plate. However, the deflection of this region is about 0.015 in. so that, for a sheet thickness of 0.007 in., the assumption that the deflection is proportional to the load is certainly not valid. Here we see that this more exact solution also has its limitations. It is thus still a matter of uncertainty whether or not in practice the value of the maximum deflection calculated by the authors is really better than the writer's approximation, which requires no more than a few minutes of calculation.

The writer must object against the statement by the authors, that the curve showing the agreement between his approximation and the experiments by Wildhack and Goerke (cf. Fig. 7 in the writer's paper[8]), was found "when adjusted on the basis of one empirical coefficient derived from the NBS experimental work." This is certainly not true and must be caused by some regrettable misinterpretation of his work. As shown in the writer's paper[8] the formulas given lead directly to a definite deflection, whether right or wrong but without *any* adjustment.

L. E. Wood.[11] The paper has been read with great interest, and the following comments, while perhaps departing to some from the general trend of the paper, are thought to be applicable in a broad sense.

The Friez Instrument Division of the writer's company has manufactured a large number of diaphragms, many of which are, in general, somewhat similar to the National Bureau of Standards Shape 1. Over a period of approximately 20 years, our diaphragms have been made of three principal materials, namely, phosphor bronze, which was replaced during World War II by berylium copper, owing to its superior elastic properties, and

[7] Chief Engineer, Philips Research Laboratories, Eindhoven, The Netherlands. Mem. ASME.

[8] "Design of Corrugated Diaphragms," by J. A. Haringx, published in this issue of the Transactions, pp. 55–64.

[9] "On Highly Compressible Helical Springs and Rubber Rods, and Their Application for Vibration-Free Mountings," by J. A. Haringx, thesis, Technological University at Delft, The Netherlands, 1947; *Philips Research Reports*, vol. 3, 1948, pp. 401–449.

[10] "Elastic Stability of Flat Spiral Springs," by J. A. Haringx, *Applied Scientific Research*, vol. 2, series A, 1949, pp. 9–30.

[11] Chief Engineer, Bendix Aviation Corporation, Baltimore, Md.

which, in turn, in recent years, has been largely replaced by Ni-Span "C," primarily because of its superior thermoelastic properties. During this period, somewhere between one and two-million diaphragms have been produced and those made today are greatly superior from the standpoint of performance and uniformity over those made 10 to 20 years ago. However, the improvements lie mostly in the realm of better materials and closer process control, rather than in improvements in fundamental knowledge as to the design of diaphragms.

Based on ideas gathered from reading the National Bureau of Standards paper and our own experience, it is thought that perhaps diaphragm-development work could be simplified a little if the following generalizations are acceptable:

1 A diaphragm is a combined spring and fluid barrier.

2 The properties required as a satisfactory fluid barrier may be taken for granted in so far as the material of the diaphragm itself is concerned.

3 The physical properties of the material affecting its use as a diaphragm are the same as those affecting its use in any spring application.

4 The properties which determine the excellence of the material as a spring, such as chemical composition, modulus of elasticity, thermoelastic modulus, hardness, microstructure, etc., are subject to reasonably exact determination and analysis.

5 There appears to be no reason, assuming a material can be formed into the necessary shape for a diaphragm, that its performance as a diaphragm would not bear the same relationship to its physical properties as its performance as a conventional spring.

6 In other words, diaphragms having identical geometric configurations should behave in relation to one another in quite direct relationship to the readily measured physical properties of the materials.

7 Consequently, significant research on diaphragm shapes should be possible, using one material having known and carefully controlled characteristics.

We do not have detailed and extensive laboratory data, verifying the foregoing, since as a result of practical necessity it has been necessary usually to vary several factors simultaneously during the transition from one material to another, but would like to suggest it for what it may be worth.

In general, our experience has agreed with that found at the Bureau of Standards in relation to the amount of motion that can be obtained from diaphragms and the general characteristics of behavior. The references in the paper, with regard to center loading and free versus clamped diaphragms, apply to areas where we feel further work is needed as well as on the more broad aspects of the diaphragm problem.

Authors' Closure

Dr. Haringx has again contributed valuable new data in Fig. 21 showing the closeness with which his approach can predict deflections of diaphragms having shapes admittedly somewhat unsuitable to his approach. In the present paper of Haringx the results which he obtained in this case for stresses as well as for deflection are surprisingly good. These results again confirm the usefulness of his formulations in diaphragm design.

We explained in the third and fourth paragraphs following Equation [7] that we computed the deflection for a loading of 15 psi in order to compare results with those of Grover and Bell, but we pointed out that the entire mathematical solution was limited to the linear range. Some confusion appears to be inescapable since our (linear) calculations cannot apply to the central part of the diaphragm for loading of 15 psi. However, if both our results and those of Grover and Bell were scaled down linearly, by a factor of, say, 5 or 10, then the comparison would be equally valid in the outer parts of the diaphragm, but Grover and Bell's curve would be in error in the central portion because of applying a linear scaling down to a nonlinear solution. Since Haringx' approximation tacitly implies a "more or less" flat plate in the central region, a better comparison would be obtained if horizontal lines were drawn to all curves of Fig. 21, intersecting them at a radius of 0.35 in. We may agree that it is yet to be proved by further comparison of experiment and calculations as to whether the computation is more accurate than Haringx' approximation, but to be meaningful the comparisons must be made on truly comparable conditions. (Incidentally, if the "exact" calculation were made on the basis of a rigidly reinforced central disk, slight changes would result in the deflection of the outer part as a result of the changed boundary condition. This might be true also, to some extent, for Haringx' approximation.)

The authors regret the statement objected to by Haringx. The sentence should have read: "Haringx was able to derive a curve which would predict the performance of the NBS Series (Shape No. 1)." The "adjustment" referred to the following sentence on the tentative and inconclusive attempts, at NBS, to test Haringx' formulation for other shapes.

Mr. Wood's generalizations appear quite reasonable and we certainly concur with the suggestion that further work is needed with respect to central loading and "free" versus "clamped" diaphragms, since these factors are of great importance in practical design work.