July 24, 1962 | W. HAUSAMMANN | 3,045,705

VARIABLE NOZZLES, IN PARTICULAR LAVAL NOZZLES FOR WIND TUNNELS

Filed Sept. 11, 1956 | 4 Sheets-Sheet 1

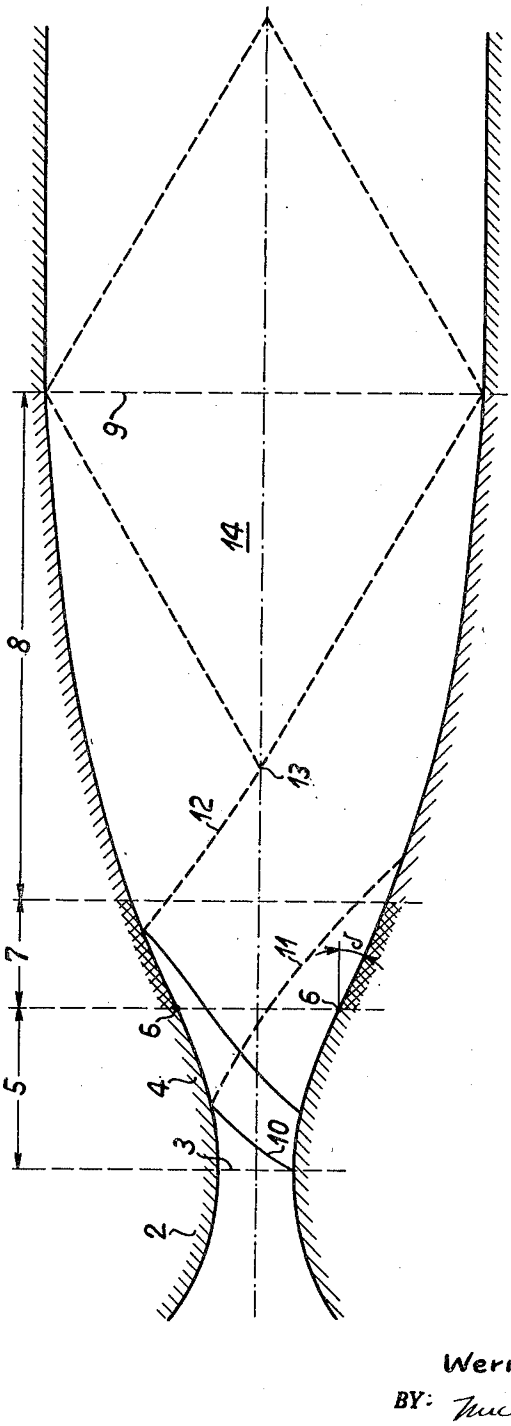


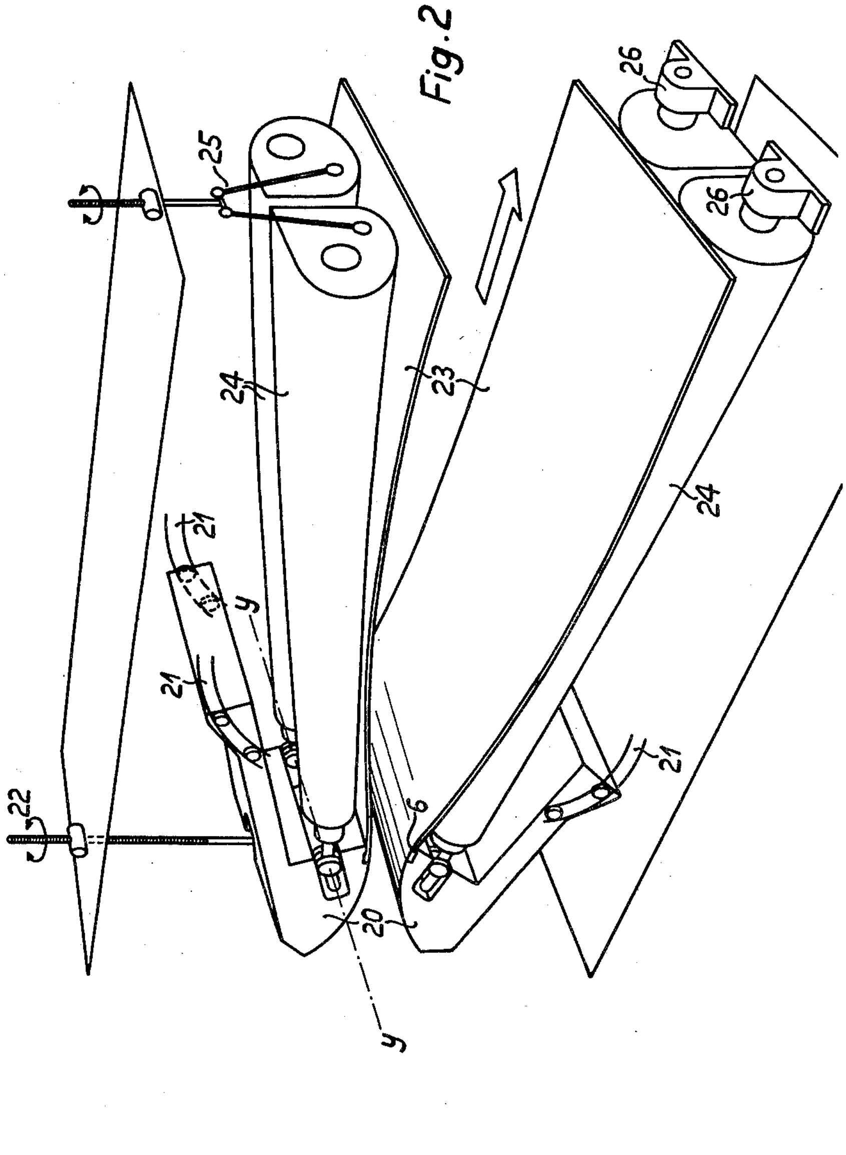
Fig. 1

INVENTOR:
Werner Hausammann
BY: Michael S. Striker
agt.

July 24, 1962 W. HAUSAMMANN 3,045,705

VARIABLE NOZZLES, IN PARTICULAR LAVAL NOZZLES FOR WIND TUNNELS

Filed Sept. 11, 1956 4 Sheets-Sheet 2



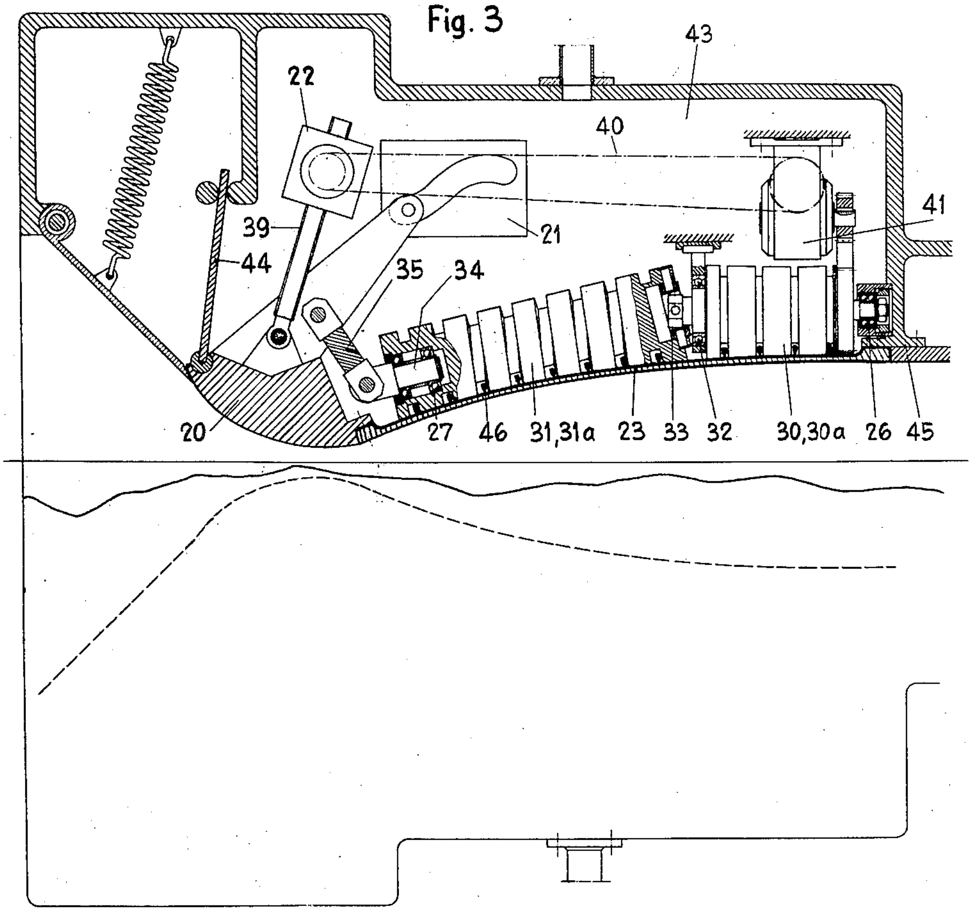
INVENTOR:
Werner Hausammann
BY: Michael S. Striker
Agt.

July 24, 1962 W. HAUSAMMANN 3,045,705

VARIABLE NOZZLES, IN PARTICULAR LAVAL NOZZLES FOR WIND TUNNELS

Filed Sept. 11, 1956 4 Sheets-Sheet 3

Fig. 3



Inventor:
Werner Hausammann

by:
Michael S. Striker
Attorney

July 24, 1962 W. HAUSAMMANN 3,045,705

VARIABLE NOZZLES, IN PARTICULAR LAVAL NOZZLES FOR WIND TUNNELS

Filed Sept. 11, 1956 4 Sheets-Sheet 4

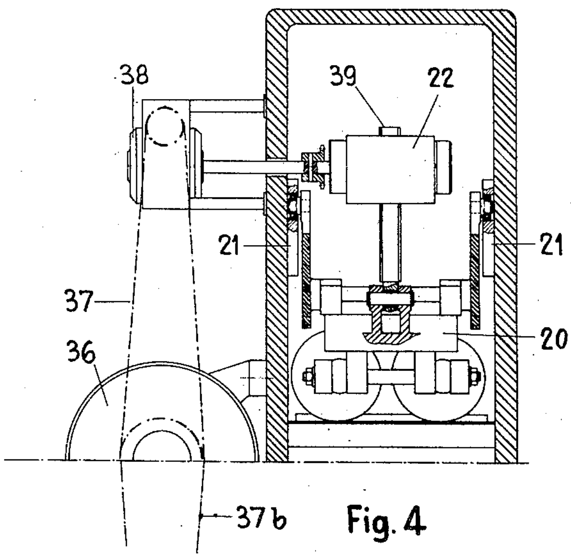


Fig. 4

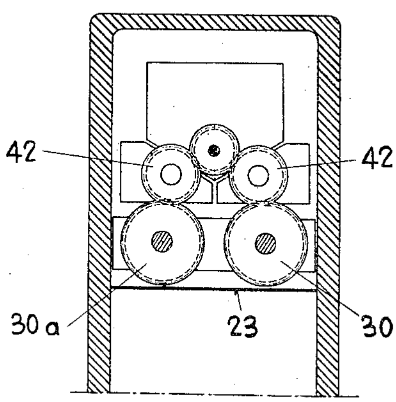


Fig. 5

United States Patent Office

3,045,705
Patented July 24, 1962

1

2

3,045,705

VARIABLE NOZZLES, IN PARTICULAR LAVAL NOZZLES FOR WIND TUNNELS

Werner Hausammann, Dufourstrasse 117, Zurich 8, Switzerland

Filed Sept. 11, 1956, Ser. No. 609,314
Claims priority, application Switzerland Sept. 12, 1955
12 Claims. (Cl. 138—45)

My present invention relates to improvements in variable nozzles, in particular Laval nozzles for wind tunnels, and the main object of the invention is to make provision for adjusting a nozzle form calculated for all the desirable Mach numbers in a certain range more accurately and more quickly than has been attainable with means known so far.

Adjustable Laval nozzles are used generally for the most efficient exploitation of large supersonic wind tunnels, being charged with the task of producing a parallel and shockfree supersonic flow in the test section proper, i.e. in the vicinity of the model to be tested.

Various designs are known today which allow to vary the shape of nozzles for the purpose of attaining different supersonic Mach numbers.

In one of these known designs a set of exchangeable nozzle blocks is used which, however, afford only discrete Mach numbers and not a continuous overlap of the entire Mach number range for which the wind tunnel has been designed, with the disadvantage that relevant flow phenomena on the model are missed. Moreover, the exchange of the blocks requires much time.

Amongst the continuously variable nozzles, the sliding nozzle block has attained some importance. In these nozzles, normally a one-sided nozzle block is shifted in the flow direction so that the block is situated in a different position for each Mach number. Such nozzles, however, have the disadvantage that their contours afford a uniform Mach number distribution in the test section only in two or three positions and give only an approximate flow in the intermediate positions. Such a solution, however, is never quite satisfactory. Further, the sliding nozzle block leads to inconveniently long nozzle structures which, furthermore, are unfavorable as to friction losses and lead to excessively thick boundary layers on the walls. The nozzle quality thereby is impaired and substantial corrections are required on the contours which are correspondingly unreliable and only empirically definable.

Nozzles having deformable contours also are known. These nozzles comprise flexible plates on two opposite sides, which are movable between the other walls which are substantially parallel to each other. Within certain limits, defined by the permissible elastic deformation of these plates, the latter may be continuously deformed for all Mach numbers of the tunnel range.

The mechanism used for deformation so far comprises a great number of threaded spindles standing essentially at right angles to the plate contours, which spindles are individually adjustable in dependence on the Mach number. Smooth, nonthreaded spindles controlled by individual cams may also be used. In accordance with the necessarily limited number of spindles, the flexible plates are supported only at discrete points, which entails unfavorable consequences. With respect to the plate thickness, a compromise always has to be made. In the case of a very thin plate, it may become wavy between the supporting spindles, whereas thick plates, on account of the permissible curvatures, lead to long nozzles and a great number of spindles.

Further, said spindle design is expensive and very complicated, in particular with regard to the adjustment to different Mach numbers. Such adjustment, in the case of manual spindle setting, requires a repetitious procedure in several steps in order to avoid local overstressing of the plates, for which purpose, by the way, safety features have been incorporated in known designs, but which again are costly and complicated and may cause difficulties. When these safety features fail in operation, there is the risk of a permanent plate deformation. The repetitious procedure when changing the Mach number is, of course, correspondingly slow, requiring approximately 15 to 30 minutes for passing through a somewhat larger Mach number range.

With a view to reducing the number of spindles, solutions have been proffered which involve variable thicknesses of the flexible plates. These solutions, however, are difficult for calculation and costly in manufacture. The objection of difficult calculation quite generally applies to the flexible plate in combination with spindles. It is true that automatic program-controlled spindle mechanisms are known too, which overcome the objection of the slow adjustment rate, but they are even more expensive and susceptible to trouble and still do not eliminate the dilemma between undesirably long nozzles and the never quite avoidable waviness between the spindles.

The present invention aims to overcome said disadvantages. The present nozzle comprises adjustable supporting means with the aid of which at least one nozzle wall is supported, and is characterized by the fact that the adjustable supporting means extend along the flexible nozzle wall and are in contact with this wall along at least one predetermined supporting curve so that the geometrical nozzle shape is continuously changed in a predetermined manner by the adjustment of the supporting means.

One form of the invention is shown, by way of example, in the accompanying drawing, in which—

FIG. 1 shows schematically the adjustable walls of a nozzle in section;

FIG. 2 depicts the adjustable Laval nozzle without sidewalls;

FIG. 3 is a fragmentary partly sectional side elevational view of another embodiment of a nozzle according to the present invention;

FIG. 4 is a transverse sectional view of the upper half of the nozzle showing structure located adjacent the front end thereof;

FIG. 5 shows a fragmentary transverse sectional view of driving structure adjacent the right end of FIG. 3 for driving the adjusting rollers.

The parts essential, from the aerodynamic point of view, to a Laval nozzle are schematically shown in FIG. 1. In a continuously tapered subsonic portion **2** (Mach number <1) a fluid is accelerated until in the least nozzle section **3** the sonic velocity thereof (Mach number $=1$) is reached. In an adjoining supersonic portion **4** of the Laval nozzle, the fluid is further accelerated to supersonic velocity (Mach number >1). Supersonic portion **4** is made up of an expansion portion **5**, an extinguishing portion **8** and an intermediate transition portion **7** which commences at the point of inflexion **6**.

The nozzle portions **7** and **8** lying downstream of point **6** serve for extinguishing the so-called expansion waves. Only by cancelling or extinguishing the Mach waves originating in expansion portion **5** on the wall contours, i.e. preventing the reflection thereof, can a shockfree and parallel flow arise in a test rhombus **14**.

Shaping of the extinguishing portion **8** in dependency on the wall contour of expansion portion **5**, which contour may be freely chosen within certain limits, is done according to known methods of aerodynamics. With each Mach number there is associated in the test rhombus **14** another nozzle contour having another cross-sectional ratio between least cross-section **3** and test cross-section **9**.

Since measurements will be made at different Mach numbers, the nozzle contour has to be variable. A variable nozzle contour is attained according to FIG. 2 as follows:

The expansion portion up to the point of inflexion **6** comprises a non-deformable inlet section **20**. When changing the Mach number, section **20** is turned about an axis of instantaneous rotation which moves along a curve for the entire Mach number range. The inlet section is guided in predetermined tracks by rails **21** when changing the Mach number, and it is adjusted for example by means of spindles **22**. The shape of extinguishing section **8** is imparted to a relatively thin plate **23** by means of parallel rollers **24** of appropriate shape.

The configuration of the rollers **24** is chosen so that each of the curves along the lines of contact of the rollers with the walls or plates **23** corresponds to a predetermined Mach number. By turning the rollers **24** about their longitudinal axes, respectively, the entire desired portion of the Mach number range is continuously traversed and the walls are given their appurtenant shape in accordance with each Mach number set. Since the roller surfaces have a continuous form, the form of the walls also is continuously changed and any desired Mach number lying within the desired range may be set.

When the rollers **24** are rotated, inlet section **20** has to be adjusted synchronously. Since the first bearing **26** is fixed in space and the roller axle is self-aligning, a second bearing of the roller mounted in section **20** and not movable in the direction of the roller axis normally moves along the periphery of a circle. If, however, the second bearing is arranged so as to be movable in direction of the roller axis, it follows a track of which the envelopes are circles having their centers on the instantaneous transverse axis of the inlet section.

The active range of the rollers suitably lies in a rotary angle range of zero to approximately 360°.

The plates **23** are clamped in front in said section **20** and, in the rear, at the commencement of test section **9**.

The additional possibility of turning the longitudinal axis of the roller about a transverse axis *y—y* represents a possible solution of simple kinematics of the installation. Said kinematics require from the nozzle shape that the expansion parts for the various Mach numbers result from one and the same contour, solely by rotation about instantaneous centers. In order to afford, for expansion part **5**, radii of curvature on section **20** which are not too small, which otherwise would lead to an unsteady boundary-layer development, the contours are designed for double reflections, i.e. the expansion waves of the fixed contour emitted immediately after the narrowest cross-section are not cancelled at once at their first impingement but only after reflection on the fixed expansion part **5** in the flexible extinguishing portion **8**.

The flexible plates **23** thus are continuously supported over their entire free length so that no waviness arises. Therefore, thinner plate material of uniform thickness may be used and flexed to a correspondingly greater extent, which leads to short and cheaper nozzles. Some narrow cross-webs for which corresponding recesses (not shown) are provided in the rollers **24**, stiffen the thin plates transversely. In place of a long roller, a plurality of rollers may be used, which are interconnected by Cardan joints, with one of the rollers, however, having an axis fixed in space, as described below in connection with FIGS. 3–5.

The rollers may rotate in individual bearings, but have to be synchronously driven.

In order to prevent plates **23** from shifting transversely upon rotation of the rolls **24**, it is of advantage to use pairs of oppositely rotating rollers **24** which support the plates **23** along two lines of contact. For intensifying the contact between rollers and flexible plates, the latter may be spring-loaded (not shown). It also is possible to make the plates **23** bear continuously over their entire length on the rollers **24** by evacuating the closed roller space.

Further a compression load acting on the plates **23** in the axial direction of the rollers also may further the contact. Such compression forces may be brought about by tension springs engaging the ends of the adjustable nozzle wall and extending across the latter, or by means of hydraulically actuated pistons (not shown) secured to the nozzle wall.

Vacuum application has two advantages: the contact pressure is continuous and distributed over the entire plate surface. A contact pressure may be set up or controlled which is the same for all the plate positions. It is further possible to still further reduce the disturbing influence of the boundary layer in the corners between flexible plates and fixed walls by evacuating said layer.

The nozzle-adjusting mechanism **22, 25** may be hydraulically, pneumatically or electrically actuated, the position of the rollers and thus the nozzle shape and Mach number always being indicated to substantially facilitate the accurate adjustment to a desired Mach number. To adjusting means **25** are connected the two rollers **24**. When turning the spindle of means **25**, the rollers **24** also are turned via eccentrically located setting levers. A hydraulic or pneumatic control is especially suitable, as it permits in a particularly simple way to preselect the Mach number to be adjusted next and to set thereby the nozzle quickly and accurately, which constitutes a further advantage of this solution. The rollers can be quickly turned so that in a few seconds the entire Mach number range may be traversed. This particular property affords, especially in the case of intermittent wind tunnels, the great advantage that the model and its mounting are protected from shock loads when starting and stopping the tunnel. Further, when the model has been adjusted, measurements in function of the Mach number may be quickly made for the determination of possible critical Mach numbers or flow conditions.

In place of the form of invention shown and described which comprises a rigid inlet section **20**, all-flexible walls may be provided. In such case, the rollers **24** have to extend also over the section **20**.

In the embodiment of FIGS. 3–5 each of the rollers instead of being in the form of a one-piece elongated roller is composed of a pair of roller portions. FIGS. 3–5 show the upper pair of rollers which cooperate with the upper flexible wall **23**, and each of these rollers has a rear portion **30**, **30*a*** and a front portion **31**, **31*a*** inclined with respect to the rear portion. The rear roller portions **30** and **30*a*** are each carried by a pair of stationary bearings **26** and **32** which provide each rear roller portion with a stationary turning axis. The front roller portions **31** and **31*a*** are connected with the rear roller portions by universal joints **33**, respectively. The end of each front roller portion which is distant from the universal joint is supported for rotation by a bearing **27** which cannot shift axially but which is capable of turning about the universal joint. Each bearing **27** is carried by a pin **34** which is pivotally connected to one end of a link **35** whose opposite end is pivotally connected with the non-deformable inlet section **20**.

The pair of rollers **30**, **31** and **30*a***, **31*a*** are turned in synchronism in opposite directions, and this turning is derived from a motor **36** (FIG. 4) which drives a pair of sprocket wheels one of which cooperates with the chain **37** which serves to transmit the drive to the upper pair of rollers and the other of which cooperates with the chain **37*b*** to transmit the drive to the lower pair of rollers. The structure which controls the curvature of the lower flexible wall is identical with that shown in the drawing for controlling the curvature of the upper flexible wall **23**. The chain **37** actuates a transmission **38** which in turn actuates a spindle drive **22** for axially shifting the spindle **39**. For example, the shaft extending from the drive **38** to the drive **22** may be connected in the housing of the drive 22 to a bevel gear meshing with a second bevel gear provided with inner threads which are in threaded engagement with the threads of the spindle 39 so that rotation of the second bevel gear will serve to axially shift the spindle 39, and in this way the nozzle section 20 will move up and down. An extension of nozzle section 20 rises in the curved guideway of the guide 21, so that in this way axial shifting of the spindle 39, which is pivotally connected at its bottom end to nozzle section 20, results in tilting as well as raising and lowering of the section 20.

The drive 22 additionally serves to drive a chain 40 which actuates a drive 41 for turning the pairs of rollers simultaneously in opposite directions. As is apparent from FIG. 5, the transmission 41 operates through a pair of intermediate gears 42 on gears fixed coaxially to the rear ends of the rollers. The simultaneous turning of the pairs of rollers in opposite directions serves to prevent lateral shifting of the flexible nozzle walls 23.

The chamber 43 (FIG. 3) in which the pair of rollers are located is sealed at its front end by sealing plate 44 and at its rear end by the fixing of the rear end of the plate 23 to the support 45. The side edges of each plate or wall 23 can slide up and down with respect to the vertical nozzle walls. The chamber 43 is evacuated by being placed in communication with the vacuum pump or the like, and by this evacuation each plate or wall 23 is continuously maintained along substantially its entire length in engagement with the pair of rollers which control its curvature.

The plate 23 (FIG. 3) is provided with transverse ribs 46 which serve to stiffen relatively thin flexible wall 23, and the rollers have annular grooves which receive the ribs.

The use of vacuum to maintain the flexible walls in engagement with the rollers is of advantage since in this way the pressing of the walls against the rollers takes place continuously along the entire flexible wall. By controlling the vacuum the pressure of the flexible walls against the rollers can be controlled and adjusted in all positions of the flexible walls. The vacuum serves in addition to remove the boundary layer from the interior of the nozzle.

I claim:

1. In an adjustable wind tunnel nozzle, in combination, at least one elongated flexible wall having an inner surface defining part of a wind tunnel nozzle and having an outer surface opposite from said inner surface, said wall extending longitudinally along the nozzle; and means extending longitudinally along said flexible wall and engaging said outer surface thereof for controlling the curvature of said wall, said means being turnable about at least one axis which extends longitudinally with respect to said wall and said means having an outer surface engaging said outer surface of said wall and provided with different longitudinal contours in different radial planes, respectively, which include said axis so that the curvature of said wall will change when the angular position of said means with respect to said axis changes.

2. In a nozzle as recited in claim 1, said means including a pair of roller portions arranged in end to end relation and inclined one with respect to the other.

3. In a nozzle as recited in claim 2, a universal joint interconnecting said roller portions.

4. In a nozzle as recited in claim 3, means for changing the inclination of one of said roller portions, the other of said roller portions being turnable about a stationary axis.

5. In an adjustable wind tunnel nozzle, in combination, at least one elongated flexible wall having an inner surface defining part of a wind tunnel nozzle and having an outer surface opposite from said inner surface, said wall extending longitudinally along the nozzle; and elongated roller means extending longitudinally along said flexible wall and engaging said outer surface thereof for controlling the curvature of said wall, said roller means being turnable about its axis and having an outer surface engaging said outer surface of said wall and provided with different longitudinal contours in different radial planes, respectively, so that when said roller means is in different angular positions it will have different longitudinal contours in engagement with said outer wall surface for giving the latter different curvatures.

6. In a nozzle as recited in claim 5, said roller means providing a gradual change in the curvature of said wall during turning of said roller means from one angular position to another angular position.

7. In a nozzle as recited in claim 5, suction means acting on said wall for maintaining the latter in engagement with said roller means.

8. In a nozzle as recited in claim 7, said suction means also removing a boundary layer from the nozzle.

9. In an adjustable wind tunnel nozzle, in combination, at least one elongated flexible wall having an inner surface defining part of a wind tunnel nozzle and having an outer surface opposite from said inner surface, said wall extending longitudinally along the nozzle; and a pair of elongated parallel roller means extending longitudinally along said flexible wall and engaging said outer surface thereof for controlling the curvature of said wall, said pair of roller means having outer surfaces engaging said outer surface of said wall, the outer surface of one roller means being symmetrical with respect to the outer surface of the other roller means and each of said roller means being provided at its outer surface with different longitudinal contours in different radial planes, respectively, and said pair of roller means being substantially coextensive and located beside each other; and turning means operatively connected to said roller means for turning the same simultaneously in opposite directions through equal angles, said pair of roller means having at any instant identical longitudinal contours in engagement with the outer surface of said flexible wall, so that the curvature of the latter will be different at different angular positions of said pair of roller means.

10. In an adjustable wind tunnel nozzle, in combination, at least one elongated flexible wall whose curvature is to be controlled, said wall having an inner surface defining part of a wind tunnel nozzle and having an outer surface opposite from said inner surface, said wall extending longitudinally along the nozzle; at least one elongated roller of substantially the same length as said wall extending along said wall and longitudinally engaging the outer surface thereof along almost the entire length thereof without interruption between the ends of said roller, the outer surface of the latter having different longitudinal contours in different radial planes; and turning means operatively connected to said roller for turning the same to a predetermined angular position to place a predetermined longitudinal contour of said outer surface thereof in engagement with said outer surface of said wall to control the curvature thereof.

11. In an adjustable wind tunnel nozzle, in combination, at least one elongated flexible wall whose curvature is to be controlled, said wall having an inner surface defining part of a wind tunnel nozzle and having an outer surface opposite from said inner surface, said wall extending longitudinally along the nozzle; elongated roller means extending longitudinally along the outer surface of said wall and engaging the latter outer surface for controlling the curvature of said wall, said outer surface of said roller means having different longitudinal contours in different radial planes so that the curvature of said wall will be different in different angular positions of said roller means; and means operatively connected to said roller means for changing the inclination thereof while said wall remains in engagement with the outer surface of said roller means.

12. In an adjustable wind tunnel nozzle, in combina-

tion, at least one elongated flexible wall having an inner surface defining part of a wind tunnel nozzle and having an outer surface opposite from said inner surface, said wall extending longitudinally along the nozzle, said wall being thin and having stiffening ribs at its outer surface extending transversely across said wall; and an elongated roller extending longitudinally along said wall and engaging said outer surface thereof between said ribs, said roller being formed with annular grooves which respectively receive said ribs and said roller having at its outer surface different longitudinal contours in different radial planes so that said wall by engagement with said roller will have different curvatures in different angular positions of said roller, respectively.

References Cited in the file of this patent

UNITED STATES PATENTS

2,462,953	Eaton et al.	Mar. 1, 1949
2,472,949	Jackson	June 14, 1949

2,486,287	Jackson	Oct. 25, 1949
2,546,673	Mattix et al.	Mar. 27, 1951
2,570,129	Johnson	Oct. 2, 1951
2,590,215	Sausa	Mar. 25, 1952
2,625,008	Crook	Jan. 13, 1953
2,696,110	Eggers	Dec. 7, 1954
2,709,917	Bruynes	June 7, 1955

OTHER REFERENCES

"AFARD" (AG 15/P6), "Papers Presented at the Fifth Meeting of the Wind Tunnel and Model Testing Panel," Schevenigen Netherlands Agard Conference, May 3–7, 1954 (TL 567 W 5N6P), pp. 130 and 146. (Copy in Patent Office Scientific Library.)

"AGARDograph 3"—"A Summary of the Techniques of Variable Mach Number Supersonic Wind Tunnel Nozzle Design," by J. T. Kenney and L. M. Webb, October 1954 (TL500 N6 No. 3), pp. 4 and 73–80. (Copy in Patent Office Scientific Library.)