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STUDIES ON FLOW GENERATED NOISE FROM CORRUGATED TUBES

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Corrugated tubes are used in many engineering applications such as HVAC ducts and offshore gas flexible riser pipelines since they offer greater global flexibility combined with local rigidity. It is well known that airflow through a corrugated tube generates whistling tones. The whistling is interesting because airflow through a smooth tube of similar dimensions will not generate tones. Studies on whistling in corrugated tubes is important as it not only causes an undesirable noise but it will also result in significant structural vibrations due to flow-acoustic-structure interaction. In this work, the experimental studies are carried out on the corrugated tubes to measure the whistling frequencies, sound pressure levels and input acoustic impedances. Influences of various geometrical parameters such as total length of the tube, number of corrugations, inlet and exit conditions on the whistling are studied. The effect of rigid and flexible wall on the whistling are also studied. It is observed that the measured whistling frequency values are in good agreement with the values obtained from theoretical models. It is noted that the measured non-flow input acoustic impedance values of corrugated tubes are about 7 to 10% less than the corresponding straight tubes. This work also investigates the efficacy of computational tools such as CFD-LES to predict the whistling and sound pressure levels for various flow rates in corrugated tubes. The study of noise reduction mechanism in corrugated tubes such as the introduction of leading and trailing edge spoilers close to cavity, slanted walls configurations at the upstream and downstream sides of the cavities and use of small strips in center of the cavities will also be presented. The simulation results indicate that CFD-LES could be used for flow noise predictions and noise reduction studies.
Keywords: Corrugated tubes, whistling

1. Introduction

Corrugated pipes and tubes are commonly used in many engineering applications because they offer global flexibility combined with local rigidity. Some of the engineering systems where corrugated tubes extensively used are the Liquefied Natural Gas storage, *Flexible risers* in offshore oil and gas industries, aerospace and automotive cabin cooling systems, vacuum cleaners and compact heat exchangers. It is found that when air flows through corrugated tubes it will emit a loud and clear “whistling sound” at some critical flow speeds. The generation of this whistling sound is interesting since the flow through a smooth pipe of similar geometry will not produce any sound. The presence of corrugations transforms the tube into an aerodynamic sound source. Whistling in corrugated tubes can cause a severe noise problem as well as severe structural vibration failure in aforementioned engineering systems. The detailed literature review on acoustics of corrugated tube is given by Rajavel et al[1]. In this paper, the experimental studies, CFD analysis using Large Eddy Simulation (LES) and passive control methods to reduce the sound pressure level are presented. The work presented here is part of the doctoral research carried out by the first author[2].

1.1 Sound Generation Mechanism in a Corrugated Tube

It is well known that "edge tone" or "whistling" will be produced when a fluid flow is impinging upon a solid surface of down stream end of a cavity. This phenomenon occurs due to the formation of free shear layer at the upstream edge of the cavity that would exhibit a self-sustained oscillation, known as impinging shear layer instability. Experiments by Nakaumara et al [3] indicated that the whistling will be generated in a corrugated tube due to this impinging-shear-layer instability. The small disturbances in the free shear layer spanning the cavity are amplified via Kelvin-Helmholtz instability. Their interaction with the trailing cavity edge gives rise to an unsteady, irrotational field, the upstream influence of which excites further disturbances to the free shear layer, especially near the cavity leading edge. This mechanism leads to flow-acoustic feed back loop which will produce the tonal sounds in a corrugated tube. At very low Mach number, the scattered field is essentially incompressible, and the feedback to the leading edge is instantaneous. When the flow velocity is close to the vortex resonance velocity where the shear-layer frequency coincides with one of the natural harmonics of the tube, the acoustic oscillation of the tube could be resonantly excited.

2. Acoustics of Corrugated Tubes: *Experimental Work*

The following experimental works are carried out to understand the whistling phenomenon in corrugated tubes. (a) Measurement of whistling frequencies and sound pressure levels in corrugated tubes with air flow. (b) Acoustic input impedance measurement in a corrugated tube using two microphone transfer function method. Two types of experimental setups are used to measure the whistling frequencies and SPL in corrugated tubes. In the first setup compressed air stored in a tank is sent through a corrugated tube via filter-mist separator-pressure gauge assembly and an acoustic plenum box. The flow velocity is measured using a hot-wire anemometer. The whistling sound in the corrugated tube is then captured using $\frac{1}{2}''$ Piezotronics microphone.

The whistling sound generated in a corrugated tube is analysed using LabView sound and vibration suite. In the second setup the air is drawn through the corrugated tube instead of sending through it by attaching a corrugated tube to vacuum cleaner. The acoustic plenum box is used in both the set ups to suppress the turbulent noise generated in the pipeline, so that the system only detect the whistling generated due to the air flow in the corrugated tube. The first set up is used to study the influence of flow velocities on whistling of corrugated tubes. The second set up is used to study the effect geometrical parameters in a corrugated tube such as change in length, inlet, exit conditions and number of corrugations for a given flow velocity.

2.1 Measurement of Whistling Frequencies and Sound Pressure Level (SPL) in Corrugated Tubes and its Comparison with Theoretical Models

Initially, two experiments are carried out for a constant velocity air flow of 7.5 m/s. In the first experiment, whistling frequencies and sound pressure level (SPL) of three types of corrugated tubes (labeled as A1, B and C) are measured. In this experiment the geometry of the corrugations (see Fig.4a) such as inner diameter, cavity depth, cavity length and cavity pitch (D_{in}, d_c, l_c, p_c) are kept constant, but the total length (L) of the tube and the number of corrugations (N) are varied. Also the inlet L_{in} and exit L_{out} lengths of the tubes are kept constant. The smooth inlet and smooth exit lengths are preserved before and after the flow encounter the corrugations (L_{Corr}). This experiment is useful for understanding the influence of total length and number of corrugations on whistling. In the second experiment the geometry of the corrugations such as D_{in}, d_c, l_c, p_c and the number of corrugations (N) are kept constant. However the total length(L), inlet(L_{in}) and exit(L_{out}) lengths of the tube are varied. This experiment is useful for understanding the effect of inlet and exit conditions, i.e, the smooth inlet and exit prior to and after the corrugations.

To compare the measured whistling frequencies with various theories, the following four equa-

tions are used.
(1) If we consider a corrugated tube as an ideal open-open ended tube, then the resonant modes are given by a well-known expression,

$$f_n = \frac{nc}{2L'} \tag{1}$$

where, c is the speed of sound, $L' = L + 1.2r$ is the corrected tube length.
(2) To predict the whistling frequency in a corrugated tube, Binnie[4] proposed a formula, in which he modelled corrugated tube as a Helmholtz resonator. Where, V_c is the volume of the corrugation, A is the area of the tube and p_c is the pitch of the corrugation .

$$f_n = \frac{nc}{2L'} \left\{ \frac{1}{\sqrt{1 + \frac{V_c}{Ap_c}}} \right\} \tag{2}$$

(3) A simple model to predict the whistling frequencies in a corrugated tube with flow is proposed by Cummings[5] (CAM model), which is given below.

$$f_n = \frac{nc}{2L'} \left\{ \frac{(1 - M^2)}{1 + \left(\frac{d_c}{R_{int}}\right)\left(\frac{l_c}{p_c}\right)\left(1 + \frac{d_c}{2R_{int}}\right)} \right\} \tag{3}$$

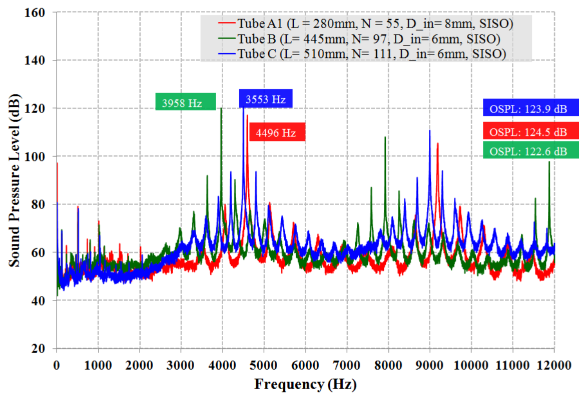
(4) Cummings also found that if $M^2 \ll 1$ then the equation Eqn. 3 can be approximated as,

$$f_n = 0.89 \frac{nc}{2L'} \tag{4}$$

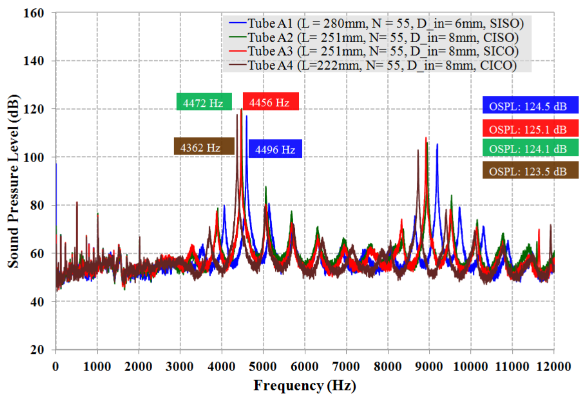
The predicted whistling frequencies in a corrugated tube using above four equations and measured values for both the experiment is given in Table. 1. Figure. 1a shows the SPL versus frequency of the various corrugated tube samples measured in the first experiment and Fig. 1b shows the measured SPL of second experiment. To study the effect of internal diameter (D_{in}), on the whistling frequencies and SPL, a third experiment was carried out. For this experiment two different types of corrugated tubes labeled as B and C are used. The details of the geometrical parameters of the tubes used are given in Table. 1. The measured frequencies, SPL and its comparison with theories are given in Table. 1. Figure 2a shows the SPL versus the frequencies for the corrugated tubes measured.

From the study it is observed that the measured whistling frequencies are in good agreement with the varies theoretical models. It is also observed that the measured SPL is between 123 dB to 129 dB. From the Table. 1 it is noted that the fundamental whistling frequencies are not generated. However, the measured frequencies are integer multiples of fundamental tones. For example, for the tube sample A1, the acoustic mode number 10 is observed. Also, if the total length of the corrugated tube (L) is changed, but other parameters are kept constant (refer Table. 1, then the generated acoustic mode number is increasing with the length of the tube when flow velocity is constant. It is inferred from Table. 1 that the measured frequencies are agreeing well with Binnie model[4]. The next best model used to predict the whistling frequencies is CAM model [5]. The Approximate CAM model and open-open tube model are in very poor agreement with experimental data. The measured whistling frequencies and SPL to study the effect of inlet (L_{in}) and exit ($L_{out)}$ conditions are also tabulated in Table. 1.

The data indicates that the observed acoustic modes are decreasing when the overall length of the tube is decreased. Also, keeping the smooth sections at the inlet or at the outlet does not alter the whistling frequencies and SPL. From the study, it is noted that even without the smooth inlet and exit section prior to the corrugation, the whistling will be generated. The observed SPL for all the four type of corrugated tube samples (A1,A2,A3 and A4) indicates that the inlet and exit conditions does

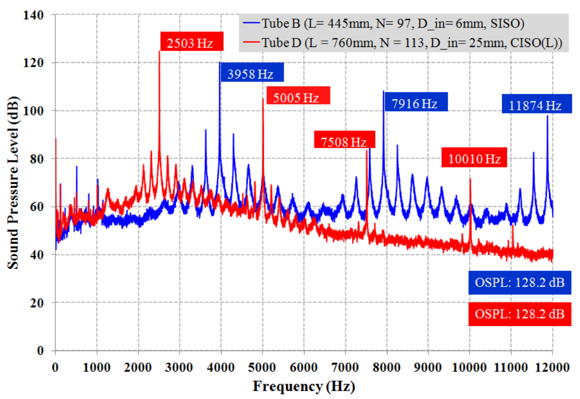


(a) Experimentally measured whistling frequencies to study the effect of total corrugated length (L) and number of corrugations (N) for three different corrugated tube samples. The flow velocity is kept constant 7.5 m/s. The microphone is kept at 25 mm from the center of the tube exit and at 90°.

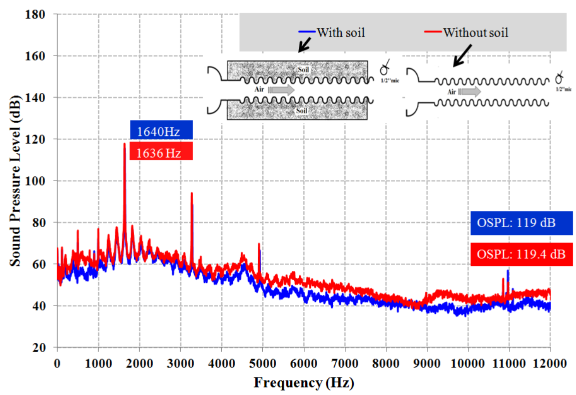


(b) Experimentally measured whistling frequencies to study the effect of inlet L_{in} and exit condition L_{out} for four different corrugated tube samples. The flow velocity is kept constant 7.5 m/s.The microphone is kept at 25 mm from the center of the tube exit and at 90°.

Figure 1: Experimental studies on corrugated tubes I



(a) Experimentally measured whistling frequencies to study the effect of internal diameter (D_{in}), i.e., size of the corrugation for two different corrugated tube samples. The flow velocity is varied. For the larger tube, flow velocity of 14.7 m/s is used and for the smaller tube the flow velocity of 7.5 m/s is used. The microphone is kept at 25 mm from the center of the tube exit and at 90°.



(b) Influence of rigid (i.e. hydrostatic pressure acting outside the tube) and flexible (i.e. no hydrostatic pressure acting outside the tube)corrugated wall on the whistling of corrugated tube (Tube D and LabView are used for experiment).

Figure 2: Experimental studies on corrugated tubes II

not have any major influence on sound productions. Table. 1 also shows the influence of different size (diameter) corrugated tube (tube B and tube D) on whistling frequencies and SPL. From the data, it is noted that to trigger the same acoustic mode then both the tubes have to experience different flow velocities. For example, to trigger the acoustic mode number 14 in small corrugated tube (8mm dia, sample B) the required flow velocity is 7.5 m/s. However to obtain the same acoustic mode number of 14, for the larger tube (25mm dia, sample D) the flow velocity of 14.7 m/s is required.

2.2 Experimental Studies on Corrugated Tube with Rigid and Flexible Wall

All the experiments in previous sections are conducted in corrugated tubes which had flexible walls. However in actual engineering applications, such as offshore gas riser pipes, the corrugated tubes wall is almost rigid because the hydrostatic pressure acting on the tube from the surrounding waters. Hence to study the effect of hydrostatic pressure on the whistling, corrugated tube is inserted concentrically on the larger empty tube and the space between corrugated tube and outer tube is filled with fine beach sand. Then the acoustical measurement was carried out for a flow velocity of 8.5 m/s and the result is shown in Fig. 2b. The measured whistling frequency of corrugated tube with and without hydrostatic pressure is almost identical which is 1640 Hz. The measured SPL value of 119 dB are also same for corrugated tube with and without soil. This experiment indicates that the cavities and flow velocities are the two main parameters responsible for whistling and not the wall conditions.

2.3 Measurement of Corrugated Tube Impedance

In this study acoustic input impedance of corrugated tube is measured and compared with the equal geometrical properties of straight tube. The corrugated tube sample D is used for this test. The measured impedance of the corrugated and straight tubes of same length are shown in Fig. 3.The impedance curves for both corrugated and straight tubes are looks similar in shape, and are characterized by sharp positive and negative peaks. The curve for the corrugated tube is seen to be shifted to lower frequency values by about 7-10%, which is closer to what was obtained during the flow test to measure the whistling frequencies and SPL. It is also noted that the shift in impedance values are getting larger when the frequencies are increased.

If the lengths and internal diameter of the corrugated and straight tubes are equal then this observed shifts are interpreted as a reduction in the effective wave speed (value "c" in Eq. 1) for the corrugated tube [6]. Hence, it can be concluded that this reduction in wave speed (and also in resonant frequency) is predominantly due to geometrical effect rather than a flow effect. The resonant frequencies for the straight tubes are defined as the ones giving zero input reactance. For a tube driven at one end and open at the other, the equation given in 1 (half-wave tube model) can be used to compute these resonant frequencies. The deeper look at the theoretical models proposed by the Binnie[4] and Cummings[5] reveals that these reduction in wave speed is accounted by incorporating the corrugated cavity parameters in the open-open tube resonant equation (Ref. Eq. 1).

Table 1: Measured and predicted whistling frequencies of corrugated tube samples. (Exp 1: All the tube samples (A1, B and C) has a $D_{in} = 0.006m, d_c = 0.001m$ and smooth inlet L_{in}=29mm and smooth outlet L_{out}=29mm. In Exp 2: All the tube samples (A1, A2, A3 and A4) has a dimension of $D_{in} = 0.006m, d_c = 0.001m$ and number of corrugations (N=55). SISO=smooth inlet and smooth outlet, i.e. both L_{in} and L_{out}=29mm; in CISO condition L_{in} is Zero and L_{out} is 29mm; SICO is reverse of CISO; in CICO both L_{in} and L_{out} are Zero. In Exp 3: ISO refers smooth inlet and smooth outlet, i.e. both L_{in} and L_{out}=29mm; CISO (L) refers corrugated inlet and smooth exit with lips, i.e. L_{in} is Zero and L_{out} is 52mm. Tube B parameters are (L=0.445m,N=97,$D_{in} = 0.006m, d_c = 0.001m, l_c = 0.003m, p_c = 0.004m$, SISO) and Tube D parameters are (L=0.760m, N=113, $D_{in} = 0.025m, d_c = 0.0045m, l_c = 0.004m, p_c = 0.006m$, CISO).)

Tube Name	Open-Open Eqn. 1	Binnie[4] Eqn. 2	CAM[5] Eqn. 3	Approx.CAM[5] Eqn. 4	Measured		Mode Number
					Frequency (Hz)	SPL (dB)	
Tube A1	587.02	444.04	454.46	522.44	4496	124.5	10
Tube A2	652.34	493.45	505.04	580.58	4472	125.1	9
Tube A3	652.34	493.45	505.04	580.58	4456	124.1	9
Tube A4	734.02	555.24	568.28	653.28	4362	123.5	8
Tube B	373.96	282.68	289.51	332.82	3958	122.6	14
Tube C	327.17	247.48	253.30	291.19	3553	123.9	15
Tube D	219.35	169.91	170.94	195.23	2503	128.2	14

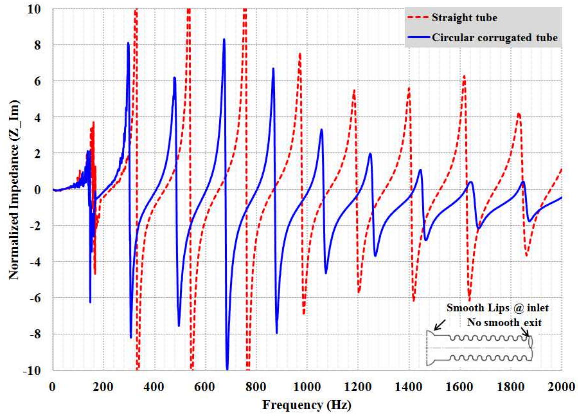
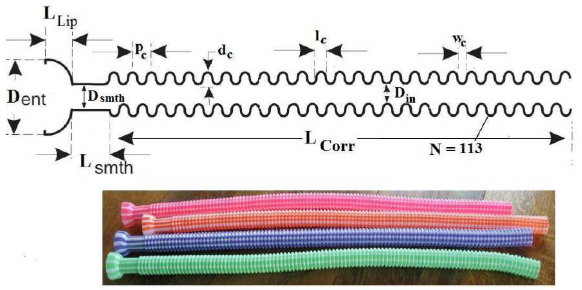


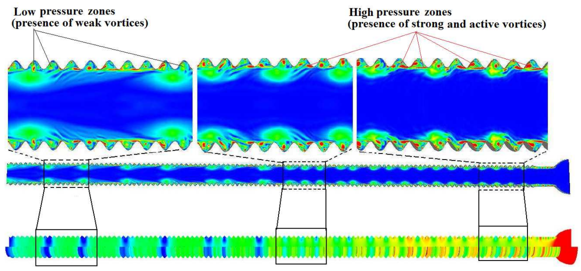
Figure 3: Experimentally measured impedance of circular cross section corrugated tube (L = 760mm) using two microphone method and LabView.

3. Acoustical Modeling of Corrugated Tube Using CFD-LES

In this study, an unsteady LES simulation is used to examine the whistling and sound pressure level in a corrugated tube for different flow speeds. The geometrical features of corrugated tube used is shown in Fig. 4a. For the study, the flow velocities are varied from 7.5 m/s, 14.5 m/s and 25.5 m/s.



(a) Geometrical details of corrugated tube used for the CFD-LES study. L_{Corr} = 715mm, L_{smth} = 32mm, L_{Lip} = 20mm, D_{ent} = 50mm, D_{in} = 25mm, D_{smth} = 25mm, l_c = 3.25 mm, d_c = 4mm, w_c = 3mm, p_c = 6.25mm, N=114.



(b) Contours of vorticity plot (1/s) and standing wave at time t=4.3s.

Figure 4: CFD simulation studies of corrugated tubes

The observed standing wave pattern of the corrugated tube for the flow velocity of 25.5 m/s is shown in Fig. 4b. The Fig. 4b clearly shows the formation of standing wave pattern in a corrugated tube. For the pressure monitoring, the probe was introduced in a center of the tube at a distance of 0.55 m from the tube inlet (axial distance). The simulated pressure oscillation frequency of 5103 Hz is correlating well with the experimental studies as given in Table 2. The vorticity plot shown in Fig. 4b indicates the presence of weak vortices at the low pressure zone of the standing wave. The presence of strong active vortices and shear layer formation and separation at the leading edge of the cavity were also noticed in the high pressure zone as shown in Fig. 4b. The whistling frequencies and SPL computed using LES were then compared with measurements and theories. Table 2 shows the simulated (using LES), predicted (using theories)and measured whistling frequencies and SPL values.

It is inferred from Table 2 that the prediction based on an open-open tube assumptions (Eqn. 1) is overestimating the whistling frequencies compared to other theories as well as LES. The theoretical models of Binnie (Eqn. 2) and CAM (Eqn. 3) were in closer agreement with CFD-LES and measurements. The predicted whistling frequencies using theories and computed value using CFD were in within 5% of the measurements. The literature review[1] indicates that there are no theoretical model available that will predict the SPL. However, it is noted that the SPL computed using FWH algorithm in ANSYS FLUENT were slightly over predicting at approximately 3 to 5 dB, but overall they are in good agreement with experiments. The results indicate that CFD-LES can be used for predicting the whistling frequencies and SPL values in a corrugated tube.

Table 2: Comparison of measured and computed (using CFD-LES) whistling frequencies of corrugated tube sample D. (L=0.760m, N=113, $D_{in} = 0.025m, d_c = 0.0045m, l_c = 0.004m, p_c = 0.006m$.)

Flow Velocity (m/s)	Mode Number	Open-Open (Eqn. 1)	Binnie[4] (Eqn. 2)	CAM[5] (Eqn. 3)	Measured		CFD-LES	
					Frequency (Hz)	SPL (dB)	Frequency (Hz)	SPL (dB)
7.5	8	1759	1359	1368	1432	119	1465	123
10	11	2412	1869	1881	1967	123	1995	127
14.5	14	3071	2379	2394	2503	128	2580	133
18	19	4168	3228	3249	3397	133	3445	136
21	23	5045	3908	3933	4112	137	4165	140
25.5	28	6142	4758	4788	5005	141	5105	144

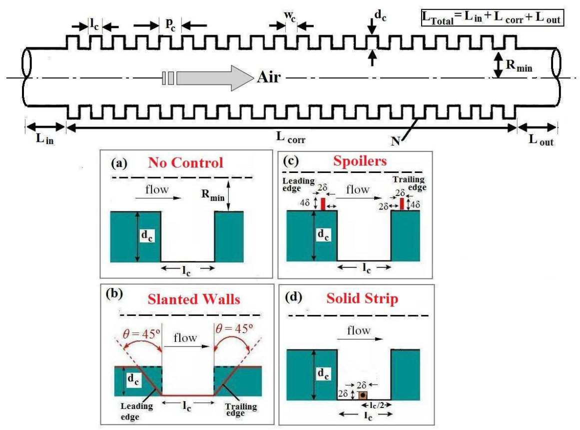
4. Passive Noise Control Studies in Flow Through Corrugated Tubes

The whistling in corrugated tubes are not only used to generate pleasant musical tones but it could also lead to detrimental effects in many engineering applications. It is observed from literature review[1] that most of recent and earlier works are focussed on understanding the whistling mechanism, prediction of resonant frequencies and whistling pressure amplitudes. Very limited number of research were focussed on noise reduction studies. Some of the passive noise reduction methods attempted are introduction of wrinkles in the tube walls, manufacturing of varying pitch cavities instead constant pitch tubes etc. Hammache et al [7] used the active control techniques to reduce the sound pressure levels in corrugated tubes. For corrugated tubes, the use of active controls are not feasible in practice and passive controls are easier to implement. The introduction of small spoilers, slanted walls at the upstream and downstream sides of the cavities and use of small block (strips) in the cavity as passive noise reduction methods are studied. Figure 5a shows the configurations of noise control methods studied for this work using LES.

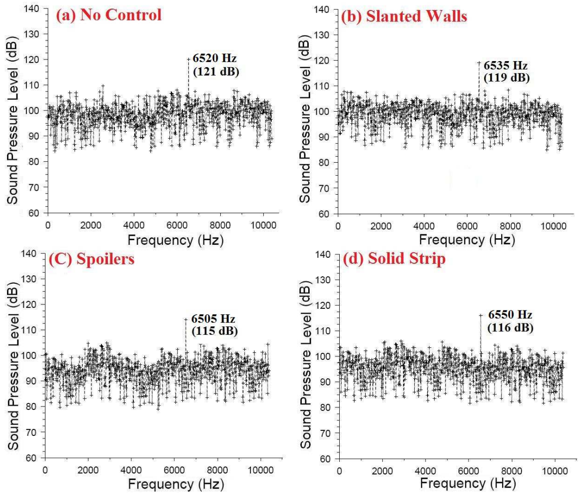
The predicted SPL versus frequency for three types of passive control methods and untreated corrugated tube is shown in Fig. 5b. It is noted from Fig. 5b that when the leading and trailing edge spoilers are used as a passive control method then the noise level reduced up to 6 dB. The use of solid strip as noise control device resulted in noise reduction of 5 dB. However the use of $45°$ slanted walls at upstream and downstream cavities as a noise control method resulted in only 2 dB. This results indicates that leading and trailing edge spoilers and introduction of solid strips at the center section of the cavities are better noise control strategies in flow through corrugated tubes. It is also absorbed that the slanted wall configuration cavities may not result in significant noise reduction. The vorticity plot indicate that use of leading and trailing edge spoilers and solid strips in the cavity effectively breaks the vortices and make them relatively weak vortices before it impinges at the trailing edge. However the vorticity plot of slated wall configurations shows that the vortices are broken or weakened and they are similar to the vortices observed in no-control corrugated tube.

5. Conclusions

In this paper the influences of various geometrical parameters such as total length of the tube, number of corrugations, inlet and exit conditions on the whistling frequencies and sound pressure level generated on corrugated tubes are studied. Measurements indicates that the whistling will be generated irrespective of outer tube is flexible or rigid. It is observed that the measured whistling frequency values are in good agreement with the values obtained from theoretical models. It is noted



(a) The predicted whistling frequencies and sound pressure levels of rectangular corrugated tubes using CFD-LES. The influence of passive noise control methods such as (a) Rectangular Tube (no control) (b) Tube with slanted corrugated cavities (c) Tube with leading and trailing edge spoilers (d) Tube with solid block (strip) at the center of the cavity.



(b) The predicted whistling frequencies and sound pressure levels of rectangular corrugated tubes using CFD-LES. The influence of passive noise control methods such as (a) Rectangular Tube (no control) (b) Tube with slanted corrugated cavities (c) Tube with leading and trailing edge spoilers (d) Tube with solid block (strip) at the center of the cavity.

Figure 5: Passive noise nontrol studies in corrugated tubes

that the measured non-flow input acoustic impedance values of corrugated tubes are about 7 to 10% less than the corresponding straight tubes. The predicted whistling frequencies and sound pressure levels for various flow rates in corrugated tubes using CFD-LES are in good agreement with the experiment and theoretical models. It is observed from CFD simulation that maximum noise reduction could be achieved by weakening the formation of vortices at the cavities by the introduction of passive control methods such as leading and trailing edge spoilers.

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